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The Application of Phosphors in Lighting

By A. H. McKEAG, M.Sc., F.R.I.C.

Research in phosphors for use in the lighting field has been pursued continuously over a period of nearly thirty years. Sulphide phosphors were already established on a manufacturing basis at the beginning of this period and the principles governing their preparation were well understood. The main problem was to develop a similar range of phosphors responsive to short u.v. radiation which would be applicable to the low pressure mercury vapour discharge lamp. A few phosphors based on the luminescent minerals, such as Willemite and Scheelite, had been prepared previously but with relatively low efficiencies. During the intervening years the range of available phosphors has been considerably extended and some of the more important developments are listed in Table 1. The halophosphate phosphors were discovered in this country in1942([1]) and quickly superseded the zinc beryllium silicate and magnesium tungstate combination, used to provide white colours in the early fluorescent tubes. They are now used throughout the world for high efficiency fluorescent tubes.

Besides their applications to the low pressure mercury vapour discharge, phosphors are also required for the colour correction of high pressure mercury vapour lamps. In these lamps the exciting u.v. radiation is distributed over a much wider range of wavelengths than in the low pressure lamp and the most suitable phosphors are those capable of utilising this radiation to the fullest extent whilst maintaining their fluorescence at the elevated temperatures at which they are required to operate. The first colour corrected H.P.M.V. lamp was marketed in this country in 1937, using a sulphide phosphor([2]) which was the most suitable of those available at that time. A nominal degree of colour correction was achieved which has been greatly improved by modern phosphors.

Preparation of Phosphors

Phosphors are crystalline inorganic luminescent materials of high purity usually containing a small quantity of one or more foreign elements, known as activators. The degree of purification necessary to achieve optimum brightness will vary with the nature of the phosphor and is generally higher for sulphide phosphors than for the more ionic compounds, containing oxygen, such as silicates, phosphates and borates. Some metals such as iron, cobalt and nickel are particularly harmful and can seldom be tolerated in amounts greater than a few parts per million of the base material.

A suitable heat treatment at a temperature which may be as high as 1,250°C is necessary to promote crystallinity in the material and to incorporate the activator in the resulting crystal lattice. Sometimes this heat treatment also promotes a reaction between two or more chemical compounds to form the phosphor. Control of ambient atmosphere during the heat treatment is an important aspect of phosphor preparation. Oxidising, neutral or reducing conditions will be employed, depending on the chemical stability of the matrix and the required valency state of the activator. Reducing conditions are maintained, for example, with most phosphors activated with tin or cerium to ensure that these activators are present in the stannous or cerous states necessary for activation, while magnesium germanate and arsenate phosphors require an oxidising atmosphere to ensure that manganese is present in the tetravalent state.

Most phosphors emerge from this critical heat treatment in the form of a lightly sintered mass which must be reduced to a narrow particle size range suitable for the lamp coating process. Reduction in size may be effected by a variety of methods, familiar in mineralogical operations including dry and wet grinding processes. The individual crystals of the phosphor are of small size, mainly below 20 microns and each crystal may be considered as an individual light source capable of transforming incident u.v. radiation into visible light.

The total production of phosphors for the lighting and television industries may be measured in thousands of tons per annum. Methods of production have therefore passed from "scaled-up" laboratory techniques to large-scale manufacturing processes, requiring the application of chemical engineering principles. Continuous precipitation, filtration and furnacing methods, for example, are widely used. Special problems of chemical and physical control have also been created in ensuring the high quality and consistency of the product. In this respect, the physical state of the ingredients which go to form the phosphor is often no less important than the chemical purity.

The author is with the Research Laboratories of The General Electric Co. Ltd., Wembley, England. The manuscript of this paper was first received on August 10, 1959. The paper was presented at a meeting of the Society held in London on November 10, 1959.

Table 1
Developments in lighting phosphors

Date	Phosphor	Application
1935-36	Zinc beryllium silicate (Mn) Magnesium tungstate	Blends used to provide white colours in high-voltage tubes and later in fluorescent lamps
1937	Cadmium borate (Mn)	Fluorescent lamps
1942	Alkaline earth halophosphates (Sb, Mn)	Superseded zinc beryllium silicate-magnesium tungstate mixture to provide high efficiency white colours in fluorescent lamps
1943	Calcium silicate (Pb, Mn)	Fluorescent lamps
1948-51	Magnesium fluogermanate (Mn) Magnesium arsenate (Mn) Barium strontium lithium silicate (Ce, Mn)	Improved colour corrected H.P.M.V. lamps
1950-59	Alkaline earth phosphates (Ti and Sn)	Fluorescent and H.P.M.V. lamps

Routine control of particle size, for example, at all stages of manufacture is an essential feature of phosphor production.

Activation of Phosphors

With a few notable exceptions, e.g. certain tungstates, molybdates and sulphides, inorganic luminiscent materials require the presence of an activator. This is usually, although not necessarily, metallic in character and includes such diverse elements as manganese, antimony, cerium, copper, lead, phosphorus, silver, thallium, titanium and tin. Some phosphors, the halophosphates for example, require two activators to obtain the desired characteristics. The key to a useful phosphor is the combination of a particular chemical matrix with a specific activator or activators. The combination will determine the sensitivity of the phosphor to different forms of exciting energy and the colour of the luminescence.

The relationship between activator concentration and light output from the phosphor usually follows a curve of the form shown in Fig.1. The falling part of the curve beyond A, corresponds to a process known as concentration quenching and is due to mutual interference of activator centres leading to energy degradation as heat. The position of the peak A varies with the class of phosphor and the method of excitation. For most sulphide phosphors the optimum concentration of activator is about one part in ten thousand and for most other phosphors about one part in a hundred. With the larger amounts, direct substitutional replacement of matrix ions by those of the activator can frequently be demonstrated by the slight displacement of X-ray reflections in an X-ray powder photograph. With sulphide phosphors, however, such direct evidence is lacking, and speculation as to the exact nature of the activator centre continues.

The range of ultra-violet wavelengths to which a phosphor will respond is of primary importance in determining its field of application. The ability to absorb u.v. radiation may not necessarily lead to the emission of light, since thermal energy

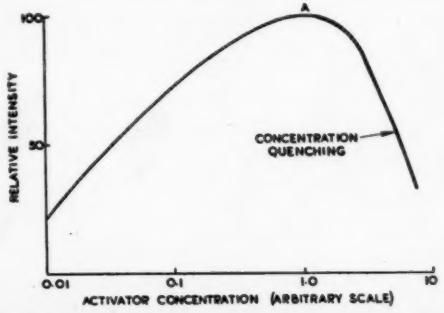
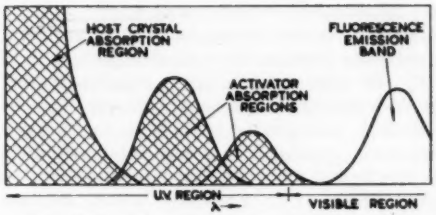


Fig. 1. Effect of activator concentration on the light output of a phosphor.



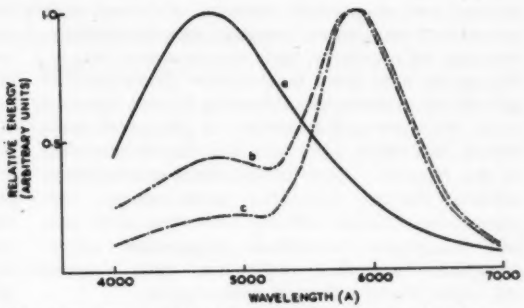
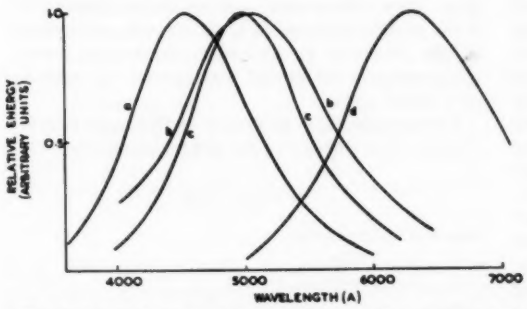


Fig. 2 (left). Schematic drawing of absorption regions of a phosphor. *Fig. 3 (right). Spectral energy distribution curves of a halophosphate phosphor activated with (a) Sb alone, (b) Sb and 1 per cent Mn, (c) Sb and 1·5 per cent Mn.*



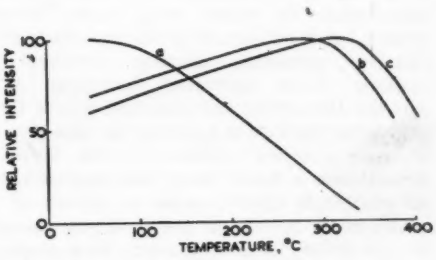


Fig. 4. Spectral energy distribution curves of tin activated phosphors; (a) Strontium pyrophosphate (Sn), (b) Barium chlorophosphate (Sn), (c) Barium pyrophosphate (Sn), (d) Strontium magnesium orthophosphate (Sn.) *Fig. 5. Temperature dependence curves of (a) Zinc cadmium sulphide (Cu), (b) Magnesium arsenate (Mn), (c) Magnesium fluogermanate (Mn).*

may be produced by competing processes in the crystal lattice. The absorption spectrum of a phosphor may be divided broadly into several regions (Fig.2) which include a short wave absorption region associated with the matrix crystal lattice, culminating in the fundamental absorption edge, and a longer wavelength absorption region usually associated with the activator. Excitation of the halophosphate phosphors by 2,537 Å radiation occurs in the latter region when antimony is used as an activator. In the presence of antimony, manganese acts as a normal activator and modifies the blue fluorescence due to antimony by introducing a second emission band (Fig.3). As the amount of manganese is increased, the manganese band predominates and the colour of fluorescence moves from blue to white and then to yellow or orange, depending on the ratio of fluorine to chlorine atoms in the matrix. The mechanism by which energy is transferred within the crystal lattice from antimony to manganese centres is of fundamental interest, and a resonance exchange process between different activator species seems a plausible explanation.

The nature of the luminescent radiation is likewise a function of the matrix-activator combination. Most phosphors give broad structureless emission bands, the position of which may vary with a given activator over a range of wavelengths. Divalent tin and manganese are particularly prolific as activators and the wide variation in spectral emission characteristics of a number of tin activated phosphors is shown in Fig.4. Some phosphors, particularly those activated by trivalent chromium, tetravalent manganese and certain rare earth elements, emit radiation with narrow banded and even line structure. Spectra of this type are frequently associated with particular electronic configurations of the activator.

Phosphors with discrete banded structure are sometimes distinguished by their outstandingly good temperature characteristics, and two important commercial phosphors, magnesium fluoger-

manate and magnesium arsenate, activated with tetravalent manganese, maintain their fluorescence emission at relatively high temperatures (Fig.5). Phosphors with good temperature characteristics are not restricted to those showing discrete spectral band structure and a number of phosphors with double and single activators are also outstanding in this respect. These include barium strontium lithium silicate, activated with cerium and manganese, calcium silicate activated with lead and manganese, strontium magnesium orthophosphate activated with tin, and barium chlorophosphate activated with copper.

Theoretical

Due to the complexities of the solid state, the exact mechanism governing the processes which occur during luminescence are still imperfectly understood. In recent years, much theoretical work[3] has been carried out on one of the simpler systems, potassium chloride activated with thallium. Good agreement has been reached between theoretical and practical results for this system but the task of applying the same procedure to more complex systems is still formidable. Nevertheless a broad theoretical approach, based on solid state theory, exists to explain at least qualitatively the effects observable in phosphors. In phosphors which exhibit photoconducting properties the mechanism follows the familiar theory of semiconductors, represented pictorially in Fig.6. It is assumed that electrons are free to move in the crystal within certain energy bands. In an insulator all the lower bands are completely filled in the normal unexcited state. In a phosphor of the sulphide class excited by ultraviolet or cathode rays, electrons are assumed to be raised to a normally empty band, known as the conduction band (B in Fig.6). The difference in energy between the highest filled band and the conduction band is usually several electron volts.

The activator is pictured as introducing new energy levels in intermediate positions and these may be the so-called ground state levels C or excited state levels C′, which are respectively close to the filled band and to the conduction band. In phosphors which belong to the sulphide class, light is emitted when electrons return from the conduction band to the activator ground state level C. In ionic crystals, light emission corresponds to electron transitions between excited state levels C′ and ground state levels C. Lattice irregularities or foreign ions may also introduce levels just below the conduction band known as trapping levels (D). Electrons which become trapped in these levels after cessation of excitation will give rise to phosphorescence. Since thermal energy is needed to release electrons from these traps they will remain in these levels indefinitely if the phosphor is cooled to very low temperatures. If the phosphor is allowed to return to normal temperatures the stored energy will be released as a bright glow.

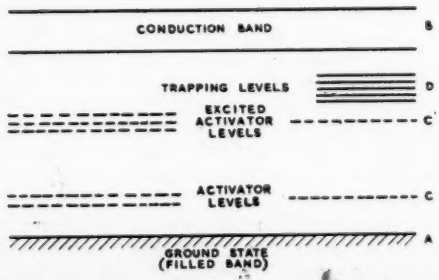


Fig. 6. Energy level diagram in impurity activated phosphors.

Phosphorescence processes of this type follow a "Power Law" decay of the general form

$$I_t = \frac{I_0}{(1+At)^n}$$

where I = Intensity.
t = Time.
A = Constant.

There is another form of phosphorescence, usually of relatively short duration, which is assumed to be due to retention of excitation energy in metastable excited states (C′) of the activator. This decay law is represented by an exponential of the form

$$I_t = I_0 e^{-at}$$

Most phosphors follow one or more exponential decay processes immediately following excitation which may then be succeeded by a power law of decay. Sulphide phosphors show the trapping effect strongly and, as would be expected, have photoconducting properties.

Application of Phosphors to Discharge Lamps

Low pressure mercury vapour lamps

The familiar fluorescent lamp provides the main outlet for phosphors in the lighting field and a list of some of the more important phosphors in present day use in these lamps is given in Table 2. Since the introduction in this country, in 1940 of the 5 ft. 80-watt lamp, efficiencies have been approximately doubled and corresponding improvements made to the lumen maintenance characteristics. The replacement of zinc beryl-

Table 2

The more important phosphors used in lamps

Matrix	Formula	Activator(s)	Colour of Fluorescence
Calcium tungstate	$CaWO_4$	—	Blue
Magnesium tungstate	$MgWO_4$	—	Blue-white
Barium phosphate	$Ba_2P_2O_7$	Ti	Blue-white
Zinc orthosilicate	Zn_2SiO_4	Mn	Green
Barium disilicate	$BaSi_2O_5$	Pb	U.V. peak at 3,500Å
Calcium halophosphate	$3Ca_3(PO_4)_2CA(F,Cl)_2$	Sb, Mn	Blue to yellow or orange, including various white colours
Calcium silicate	$CaSiO_3$	Pb, Mn	Yellow to orange-red
Cadmium borate	$Cd_2B_2O_5$	Mn	Orange-red
Magnesium arsenate	$Mg_4As_2O_{11}$	Mn	Red
*Zinc cadmium sulphide	(Zn, Cd)S	Cu	Orange
*Magnesium fluogermanate	$Mg_4GeO_6MgF_2$	Mn	Red
*Barium strontium lithium silicate	$(Ba, Sr, Li_2)_2SiO_4$	Ce, Mn	Red
*Strontium zinc orthophosphate	$(Sr, Zn)_3(PO_4)_2$	Sn	Orange

* Used in H.P.M.V. lamps.

lium silicate-magnesium tungstate mixtures by the halophosphate phosphors, for example, resulted in an immediate increase in luminous output, although it has to be admitted with some loss in colour rendition. Improvements in luminous performance since the introduction of halophosphate phosphors are due to improvements in both phosphor manufacturing techniques and methods of processing the lamp. Initial efficiencies (E_{100} hour) exceeding 66 lumens per watt can now be obtained on a production basis from 5 ft. 80-watt lamps. Higher efficiencies are, of course, possible from 4 ft. 40-watt lamps.

The most recent improvements in these phosphors arise from the knowledge that very fine particles of halophosphates are unable to absorb u.v. radiation effectively and are consequently of lower intrinsic brightness than the remainder of the powder (Fig.7). These ultra-fine particles have a high specific surface and are therefore more sensitive chemically to lamp processing and operating conditions. Furthermore, they tend to form a coating over the larger and more efficient phosphor particles which reduces their efficiency.

Ultra-fine particles are created largely as a result of the grinding and milling operations to which the powder is subjected in order to reduce the average particle size to a value which will give an acceptable coating appearance. The loss in efficiency after milling may amount to as much as 10 per cent, practically all of which may be attributed to the ultra-fine particles. The problem therefore is to eliminate these very small particles from the powder after the final milling treatment.

This can be done by special classification techniques in the sub-sieve range of sizes involved. A number of methods are available but those depending on centrifugal separations using either air or liquid media are perhaps the most suitable for quantity production. Liquid centrifugal separations are particularly effective because they enable the powder to be effectively dispersed in the liquid media even at very fine particle sizes. One form of equipment which can be used is the hydrocyclone (Fig.8) which consists of a cylindro-

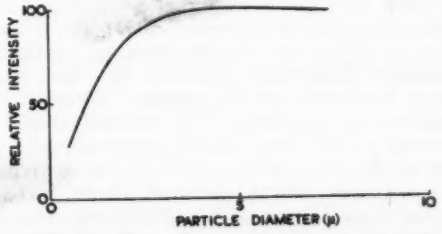


Fig. 7. Variation of brightness of halophosphate phosphors with particle size.

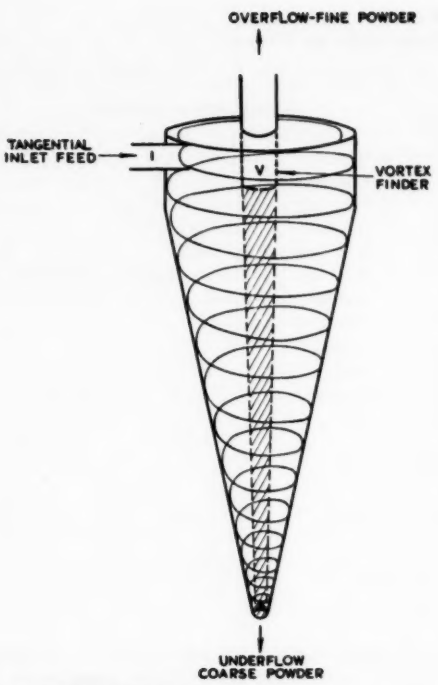


Fig. 8. *Diagram of hydroclone.*

conical vessel, provided with an inlet tube (I), asmall conical nozzle at the apex (A) and a second outlet tube, known as the vortex finder (V) fitted into the top of the vessel and projecting a short distance into the body of the vessel. Powder is fed in suspension form under pressure through the inlet tube and a spiralling motion is set up, a double vortex being formed. The coarser particles from the suspension are thrown to the walls of the cone and then travel downwards to be discharged through the apex nozzle. Finer particles travel upwards with air drawn in through the apex and are discharged from the cyclone through the vortex finder. The particle size separation achieved is dependent on the dimensions of the cyclone and the operating conditions employed. Ultra-fine particles in the range below 3 microns can be separated efficiently by means of this apparatus. The treatment of milled powders in this way enables practically all the loss in efficiency due to milling to be recovered. It is necessary with the classified powder, because of its larger average size and reduced covering power, to use an increased coating weight to obtain the full efficiency improvement.

Quantum efficiency of phosphors

It is obviously of considerable importance in this type of investigation to know, at least approximately, the maximum efficiency which is theoretically possible in a particular type of lamp. This question has been raised in a previous paper([4]) and a figure of the order of 80 lumens per watt has been estimated for 40-watt lamps having a spectral distribution similar to the British Daylight colour. A lower figure of 60 lumens per watt has been given for a spectral distribution similar to one of the phases of natural daylight.

Calculations of this kind require a knowledge of the quantum efficiency of the phosphor involved, quantum efficiency being defined as the ratio of the number of quanta emitted by the phosphor to the number absorbed. The results of measurements with normal lamp phosphors by various workers is given in Table 3([5]), and for halophosphate phosphors a value between 0.80 and 0.95 is generally agreed. There is need for a more precise value of these measurements, and an accurate determination of a suitable phosphor, such as magnesium tungstate, as a basic comparison standard has been suggested([5]). The intention would be to use this standardised value for the measurement, by comparative means, of other phosphors. Taking the measured quantum efficiency results and the calculated lamp efficiencies as a guide, there is obviously still room for appreciable improvements in fluorescent lamp efficiencies before the ultimate limit is reached.

Table 3

Quantum efficiency measurements with normal lamp phosphors

Phosphor	Excited by	Quantum Efficiency (Average of various measurements)
Cadmium borate (Mn)	2,537Å	0.72
Calcium halophosphate (Sb, Mn)	2,537Å	0.88
Calcium silicate (Pb, Mn)	2,537Å	0.70
Calcium tungstate	2,537Å	0.70
Magnesium arsenate (Mn)	2,537-3,650Å	0.85
Magnesium tungstate	2,537Å	0.87
Zinc silicate (Mn)	2,537Å	0.83
Zinc cadmium sulphide (Cu)	3,650Å	0.55

It has hitherto been assumed implicitly that quantum efficiencies greater than unity cannot be realised. In a recent paper([8]), however, it has been suggested that it may be theoretically possible to exceed this figure when certain special conditions are fulfilled. Whether results greater than unity can be achieved in phosphors of the type commonly used in discharge lamps seems questionable, and although Russian workers([7]) have, in fact, reported experimental results exceeding unity with standard lamp phosphors under 1,850Å excitation, the difficulties inherent in measurements in this particular u.v. region make confirmation of these results necessary.

Colour and colour rendering

With the wide range of phosphors now available for use in fluorescent lamps the problem of providing light sources of different colour appearance and colour rendering properties has been largely overcome. By using suitable combinations of the various phosphors, colour rendering properties similar to that provided by North sky daylight on the one hand or tungsten filament lamps on the other can be reproduced. Inevitably, however, because of the shape of the eye spectral sensitivity curve, improvements at the red or blue ends of the spectrum lead to reduced lamp efficiencies.

Lumen maintenance

Improvement in the lumen maintenance characteristics of lamps is at least of equal importance to the achievement of higher initial efficiency. Although it has not, so far, been possible to obtain an exact treatment of the mechanism of light depreciation a number of facts seem reasonably well established. Lumen depreciation is mainly the result of interaction between the phosphor particles and the excited mercury atoms on the one hand and u.v. radiation on the other. Subsidiary effects enter into the process from cathode "sputtering" and reactions between phosphor particles and the glass envelope.

The chemical constitution of the phosphor itself and the nature of the activator determine to a large extent the deterioration in luminous performance throughout life. Chemical stability of the phosphor, particularly to chemical reducing conditions, provides at least a rough criterion of its performance throughout life. In the presence of the photochemically active short u.v. radiation, chemical changes in the phosphor may occur. The effects of short u.v. radiation in the absence of mercury vapour has been demonstrated with a number of phosphors. A particularly rapid depreciation occurs with some phosphors, for example, strontium fluorophosphate, activated with tin and manganese, when exposed to 2,537Å radiation. This deterioration is accompanied by a visible discolouration of the phosphor even under vacuum conditions.

Excited mercury atoms may also contribute directly to the deterioration([8]) or indirectly by combining with free metal atoms produced during lamp processing or subsequent operation. The exact sequence of events taking place during lamp operation is difficult to determine and may vary with different phosphors, but the probability that more than one process of deterioration occurs is evident from the characteristic shape of the lumen maintenance curve (Fig.9). This shows a fairly steep initial fall, followed by a much slower deterioration. Mathematical expressions comprising a number of rate process terms have been suggested([9]) to fit this form of curve but the chemical or physical significance of the separate processes is still somewhat obscure.

Interaction between phosphor and glass surface has already been mentioned as having an influence on lumen maintenance. This is believed to be due, at least partly, to the effect of sodium ions present in the glass which are known to produce adverse effects on lumen maintenance. It is

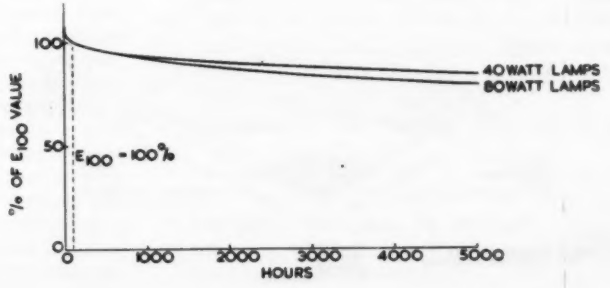


Fig. 9. Lumen depreciation curves for a halophosphate phosphor in 40- *and* 80-*watt fluorescent lamps.*

also known that such effects are lessened if the glass surface is well covered with phosphor particles or if the glass is pre-treated to remove superficial sodium.

The problem of improving the lumen maintenance characteristics of fluorescent lamps becomes more acute with lamps operating at higher loadings, when deterioration becomes more rapid. Isolation of the various effects which influence lumen depreciation with a view to providing a better understanding of the mechanisms involved is therefore of considerable importance and much work is going on in the laboratories of the large lamp companies to this end.

Phosphors for high pressure mercury vapour lamps

In the H.P.M.V. fluorescent lamp the phosphor is applied not directly to the discharge tube but to an enlarged outer envelope to keep the phosphor temperature down to a reasonable value. About ten years ago zinc cadmium sulphide phosphor was the only one available for this purpose and a moderate degree of colour correction was obtained with this material. Because the sulphide phosphors respond only to long wavelength u.v. it was not possible in this type of lamp to make use of the considerable amount of short wave energy in the H.P.M.V. discharge. The recent development of new red emitting phosphors (Table 2) with outstanding temperature characteristics and broad excitation spectra has led to a considerable improvement in the colour rendering properties of H.P.M.V. lamps, with little or no less in efficiency[10]. Lamps of efficiency greater than that of the plain H.P.M.V. lamp have also been produced abroad[11], using phosphors with predominantly yellow and orange emission colours; as might be expected, however, the colour rendering properties of these lamps are poorer than those obtained with the deep red phosphors mentioned above.

The possibility of further advances in this field depends on the development of new phosphors having still better temperature characteristics and the broad excitation spectra needed to utilise available u.v. energy from the lamps to the best advantage.

Phosphors for other forms of lighting

Electroluminescence

The phenomenon of electroluminescence was discovered by Destriau[12] following earlier work on the influence of an electric field emitted by a phosphor. Destriau showed that a specially prepared zinc sulphide phosphor can be made to emit light if it is subjected to the influence of an electric field. The techniques he described have since been elaborated by a number of workers.

The modern electroluminescent lamp (Fig.10) consists essentially of a sheet of conducting glass coated with a thin layer of zinc sulphide phosphor embedded in a solid dielectric which in turn is backed with a conducting layer. The dielectric medium may be either an organic resin, or a transparent vitreous material. Substances such as titania may also be incorporated in this medium to increase its dielectric constant and improve reflectivity.

Phosphors suitable for electroluminescence applications are of the sulphide class activated with copper and possibly additional activators, and these are distinguished from conventional sulphides by the higher activator content. This imparts a noticeable body colour to the phosphor with a consequent reduction in light output. Colours ranging from blue to orange can be obtained with sulphide or sulphide-selenide phosphors using suitable combinations of activators. Reddish colours can be obtained by the use of fluorescent

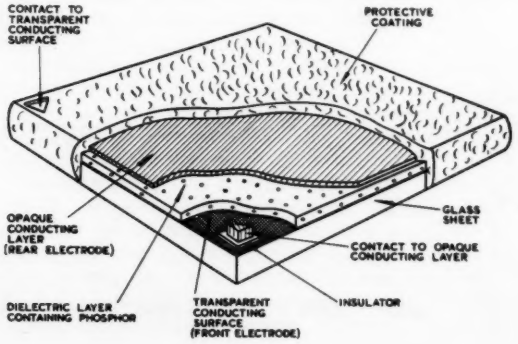


Fig. 10. *Construction of electroluminescent panel.*

organic dyes, such as rhodamine, in association with blue emitting panels. Blends of these phosphors can be used to give white or near white colours of rather poor quality.

Even with phosphors with green emission, efficiencies are disappointingly low. Efficiencies of the order of 10 lumens per watt have been quoted for phosphors of this colour under low brightness operating conditions, but under practical conditions much lower values are obtained. Under conditions of high field strength and high frequency, luminances of the order of 100 ft.-lamberts are possible, but the life and lumen maintenance of the panel under these conditions are then very poor. The possibility of electroluminescence panels becoming important as light sources is therefore remote unless major improvements are made in both efficiency and lumen maintenance characteristics. They are finding some application for specialised lighting where efficiency, high brightness, and colour are not important, such as indicator, instrument and photographic dark room lighting.

Of perhaps greater potential importance is the use of electroluminescent devices in combination with photosensitive materials such as cadmium sulphide or selenide. Light falling on the photosensitive material causes it to conduct and allows current to pass to the electroluminescent material with the emission of light. In specially designed devices this effect can be used to produce an amplified light image of the original image projected on to the photoconductive surface. The effect can also be used with X-rays to give higher brightnesses than can safely be obtained with conventional fluorescent screens. The relatively long time-constants of the photoconductive materials is, however, a disadvantage of these devices for many applications.

Radio-active krypton lamps

With increased outputs of fission products from atomic piles, radio-active krypton of mass number 85 has become available. This isotope having a half-life of about eleven years emits mainly β rays (or electrons) with a small amount of γ radiation. Sulphide phosphors can be excited by the electrons released to produce a low intensity light source needing no external power supply[12]. In its simplest form, the lamp comprises a glass bulb coated with a thin layer of a sulphide phosphor and containing a mixture of radio-active krypton and normal krypton. The low light output and high cost of radio-active krypton is obviously a limiting factor in the use of such lamps for anything but specialised indicator applications ; for example, in situations where normal electrical supplies are not available.

Conclusion

In this paper, it has only been possible to deal in any detail with phosphors for lighting applications. Phosphors for television, radar and X-ray technology are also of considerable importance ; and in the broader sense the development of phosphors may be said to have foreshadowed the rapidly developing field of semiconductors.

Phosphor research has been conducted largely on an empirical basis and none of the phosphors at present in use owe their development to a theoretical approach. The possibility of predicting a new phosphor system represents therefore a tremendous challenge to the theoretical physicist.

From the practical aspect, continued improvement in lamp performance can be expected both from the phosphors themselves and from their more efficient utilisation in lamps. Apart from progress in conventional discharge lamps, the possibility of exciting phosphors by an electric field or other means holds out prospects of interesting developments.

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Discussion

DR J. W. STRANGE: I am grateful for the opportunity of opening the discussion on this paper. I understand it was originally entitled 'Research in Phosphors' but has now been changed to 'Applications of Phosphors in Lighting'. I am very interested in both subjects so the change in emphasis is not a great disappointment for me. There must, however, be some whose main interest is in phosphor research and they may be rather disappointed. Before the meeting I referred back to the last paper on this subject given by Mr McKeag and his colleagues in 1952. Much of the material is common to both papers, but I was particularly disappointed to find that in the list of phosphors given in Table 2, only two had been added in the intervening years. Other phosphors have been developed during these years and whilst not many of them have taken a predominant part, a number of them are interesting. The halophosphate group excited by copper and tin, and those activated by cerium, numerous pyrophosphates, titanium activated magnesium fluosilicates and, if we are to cover sulphides as well, the very comprehensive work on gold activation is of considerable interest. If we are not tied down to actual commercial application of phosphors but are concerned with their technical interest a much larger number could be considered. Particular examples are the sulphate phosphors which are extremely bright initially and have an incredibly bad maintenance. This might be of absorbing interest to the theoretician.

One of the subjects referred to is the quantum efficiency of phosphors and it is stated that this question was raised in the paper by Jenkins and McKeag in 1952, when a figure of 80 lumens per watt was estimated. There was in fact at that time a very interesting discussion in which this figure was put forward by Harrison and separately by Henderson with some argument with the authors on the validity of their assumptions. This time Mr McKeag is more cautious and does not give an actual figure simply saying that there is room for improvement. While I have some sympathy with his caution I shall be interested to know if he can put a revised figure to this estimate, particularly if he could express any views on the validity of the various elements of the calculation.

Mr McKeag is also cautious on lumen maintenance and only says that there is room for improvement. This is something of first-class importance at the moment because of the development of higher loading lamps, and I think the various companies who have accumulated data should be encouraged to publish more about it. For years we have related our data to the Butler/Lowry equations and found a very good co-relation with them.

The author mentioned the modern form of the electroluminescent lamp as having a conducting glass base but there is also the metal ceramic lamp. This is a further development of increasing importance. The construction consists of the phosphor embedded in a ceramic coating on a metal layer which obviously widens the possible applications to a considerable degree. As it has the great advantage of robustness and good lumen maintenance. Secondly, in his reference to the phosphors used he rightly places the emphasis on the copper activated sulphides but he did less than justice to the importance of additional activators. The manganese copper activated sulphide is of equal importance and of great interest.

MR A. G. PENNY: We hear so much these days of the wonders of the phosphor chemists and the claim that it was as the result of their work that we got better and better lamps but, so far as I can judge, most of the efforts in that direction tend to produce lamps of more and more efficiency in terms of lumens per watt simply by a sacrifice in colour rendition. Could I ask whether there is any prospect of improving the colour rendition by means of a suitable selection of phosphor or the development of more efficient posphor, so that we can look forward to colours comparable to that of the black body but at rather more than half of the efficiency of the fluorescent tubes which are so widely used and so generally offered for sale as a good lamp for lighting purposes?

MR D. H. HOLLOWAY: This question may seem simple to phosphor chemists but it has me rather puzzled. I would like to know whether there is any reason to assume that the phosphor crystals become overloaded with increase in incident energy. Will the phosphor eventually become saturated or will it continue to increase in output with increase in incident energy?

MR FURNESS: Could Mr McKeag explain why phosphors that have a high output in the red end of the spectrum give less light as measured by a photometer as distinct from that which is detected by the human eye?

DR J. W. T. WALSH: With regard to colour rendering, my impression is that one of the principal troubles in the ordinary fluorescent lamp is strong emission by the mercury discharge somewhere in the blue or the violet of the visible spectrum, with

the result that the lamp designer pushes up the emission somewhere in the yellow or orange to counteract it. Is there any possibility of getting a phosphor which will absorb the radiation from the mercury and get rid of it or move it into the infra-red?

MR PENNY: I quite appreciate that by a suitable choice of existing phosphors we get a colour rendition that is adequate. What I really questioned was the possibility of say tailoring the emission of a phosphor to the characteristics of the eye to produce a colour rendition comparable to that obtained when the eye looked at something illuminated by an incandescent body having a smooth characteristic throughout the whole range. Even the de luxe colours are still not very good colours when regarded by the critical eye of people who are used to colour matching, the artist, the man who has to make coloured things, the person who has to decorate rooms and choose fabrics. All the fluorescent tubes of any of the colours which are available today are really imperfect in that sense. Is there any prospect of us tailoring the phosphor so that a really satisfactory colour might be possible at some reasonable sort of efficiency. With filters, one can perhaps get something quite satisfactory, but probably we get down to something like ten lumens per watt and would be better off with the tungsten filament lamp. Is there any chance of getting a good colour at say 40 to 50 lumens per watt?

MR HOLLOWAY: In a report in an American paper quite recently, I read of the use of tungsten filaments combined with a discharge tube in a fluorescent coated bulb. The filament was said to raise the temperature of the bulb and thereby gave an increased efficiency to the phosphors used on the inside of the bulb. Is there any proof of this?

The author showed a curve which seemed to illustrate the increase in efficiency with temperature, and I believe the optimum is of the order of about 300 degrees. Presumably then you would design a lamp to have a bulb temperature of 300° for an optimum red output.

DR W. E. HARPER: One matter that particularly interests me is the possible consequence for lighting practice of the development of these new phosphors for colour-corrected HPMV lamps. The colour rendering of experimental lamps that I have seen is remarkably good and if this can be achieved in production it would seem that they must materially affect both industrial and street lighting practice. I have, however, heard it suggested that the emission characteristics of the phosphors are affected by the high temperatures at which they must operate. I would like to know whether there is any change in the spectral quality of the light emitted by these lamps during their life.

THE AUTHOR (in reply): Dr Strange has mentioned the wide range of phosphors which might have been included in the paper. Although these are of general interest, it must be remembered that of the many new phosphors which are developed, few are of sufficient importance to be used commercially.

Dr Strange has also raised the question of the maximum efficiency of fluorescent lamps and the discussion following the paper by Jenkins and myself in 1952. Differences in the values quoted at that meeting arose mainly from the different spectral energy distributions chosen for the respective calculations. There are still uncertainties in some of the basic measurements used in these calculations, but if the measured values for the quantum efficiencies of the halophosphates are taken as a guide, a theoretical gain in maximum efficiency of about ten per cent seems possible with a phosphor having a quantum efficiency approaching unity.

On the question of lumen maintenance, I agree with Dr Strange that the accumulation of more fundamental knowledge is needed to throw more light on the processes which are involved. Although the Butler-Lowry equation fits the observed lumen maintenance data fairly closely, the validity of the basic assumptions need further verification.

Mr Penny raised the question of the colour rendition of lamps. With the phosphors now available, the choice lies between lamps with high efficiency and moderate colour rendition and those of good colour rendering properties at a lower efficiency level. The final compromise between these extremes is therefore largely a commercial question.

In reply to Mr Holloway, sulphide phosphors show a tendency to saturation with high levels of incident u.v. radiation, but in oxygen containing phosphors such as silicates and phosphates there is not much evidence of saturation effects. If, however, there is sufficient incident u.v. radiation to raise the temperature of the phosphor appreciably during excitation the light output might be reduced.

The observation of Mr Furness may be due to a difference in response curve of the photometer from that of the human eye.

In reply to Dr Walsh, certain phosphors such as magnesium arsenate and germanate have a strong absorption band in this region of the spectrum,

and these phosphors act as a filter for the mercury lines. They are excited by these lines to give a slightly enhanced emission in the red.

In reply to Mr Penny's further point, there seems no reason why a smoother emission curve could not be provided with a more complicated mixture of phosphors. This would resemble more closely the emission curve of a black body radiator, but in turn would lead to greater complexity in lamp manufacture.

In reply to Mr Holloway, certain phosphors such as magnesium fluogermanate become somewhat brighter as the temperature is raised, due partly to a slight change in colour towards the yellow. The overall change in light output of the lamp itself, would however be relatively small as a result of this effect.

I am doubtful if there would be a significant gain in red output by operating the lamp at the higher temperature indicated by the temperature dependence curve.

In reply to Dr Harper, the phosphors used in colour corrected HPMV lamps are stable under lamp operating conditions and the spectral qualities remain substantially constant during the life of the lamp.

Light and Productivity

By A. N. IRENS, M.Sc., M.I.E.E.

(1) Introduction

I am indeed honoured at being given the opportunity to give one of the Society's Golden Jubilee lectures. I think I am fortunate also in that circumstances have placed me in a position to speak on Lighting and Productivity from the combined viewpoints of the industrial user, the consulting engineer and the electricity supply industry.

I make no claim to be highly skilled in the science and technology of lighting, but the technical libraries and the Transactions of the Society bear testimony to the magnitude and vitality of the contribution made by members of the Society, and looking back over the fifty years I think the lighting industry can justly claim to be proud of this technical achievement.

Speaking of the present, I find that there is still considerable need and scope in our factories, shops, offices and houses for putting the knowledge we have gained into profitable practice. As to the future, given a full measure of consultation with the associated organizations and professions and wider dissemination of the facts and figures, I believe we shall see artificial lighting properly recognized and acknowledged for the important part it can undoubtedly play as a vital service to industry, commerce and to the community at large.

I have prepared the paper with the specific aim of stimulating interest in better lighting and it will best serve that purpose if it promotes constructive thought and action. To this end I have issued one or two challenges and made some recommendations.

(2) Light

Light, in partnership with seeing, plays a vital part in controlling man's existence. Whether natural or artificial it is a basic requisite around which our daily activities revolve. It ranks closely with other vital but inexpensive essentials such as air and water and, much in the same way, is taken far too much for granted. I sometimes wonder if artificial lighting and the electricity to go with it, are so inexpensive that we are inclined to lose sight of their importance. It may be that this explains why so many people still seem to be unaware of the true place of artificial lighting today in commerce and industry and appear to remain unconvinced of its potential profitability and investment value.

It may bring this situation into truer perspective if I comment that out of the 8,760 hours in a year we get the aid of daylight for only about one-half, say 4,500 hours, and that many of these (before breakfast on a summer's morning, for instance) are traditionally unsuitable times for working. The time, therefore, in each year during which we can do without artificial light falls far short of what we need in the twentieth century to meet the exacting demands of modern living and working. Over the years, civilization has brought man out of the sunlight to live and work indoors, persuaded him to turn more and more of the night into day and remorselessly imposed upon him tasks and processes of increasing intricacy and detail. Consequently, his need for more well-planned and efficient interior lighting to make his seeing easier and agreeable has steadily grown.

In laboratory and workshop the electric lighting industry has undoubtedly kept pace with this demand for better lighting—higher lumens per watt, less glare and improved colour—but unfortunately it has been hiding its 'light' under a bushel and in my view is hardly finding the most effective means of showing the users—small and large—how the knowledge gained can be put into profitable practice.

(3) Achievement and Comparison of Costs

(3.1) The incandescent lamp

It is a good thing occasionally to reflect on the past and give a thought or two to the pioneers who made artificial lighting a practical possibility. Twenty years before the turn into the present century Edison in America and Swan in this country were about to bring the incandescent lamp into practical use. It is interesting to recall that when Edison went to a power company to raise capital for his first incandescent lamp factory, his proposition was turned down because it was too risky. Yet today, world production of incandescent lamps—the common or garden lamps we use in our homes—runs to 5,000 million per annum. (100 million of these bulbs are sold annually in the United Kingdom.) Incidentally, over the intervening eighty

A lecture given at the Federation of British Industries in London on October 27, 1959, being one of a series of four Golden Jubilee lectures. The author is Chairman of the South Western Electricity Board.

years, the principle and the basic components of this form of lamp, consisting of the sealed bulb, the filament and the cap, have not been changed.

Research and manufacture during that time have brought the incandescent lamp through a series of interesting developments and improvements to become the popular shape and form in which we now recognize it as an indispensable accessory to our work. Many of us will remember the 'half-watt', introduced just before the first world war and so named to mark the achievement of providing, by means of quite a large lamp, a unidirectional light intensity of one candle for the expenditure of only half a watt of electricity, representing a conversion efficiency of about eight lumens per watt in terms of present nomenclature. Today, with tungsten filament lamps we proudly boast of 15/20 lumens per watt and so giving two to three times as much light for the same expenditure of energy. It certainly gives cause to think when we realize that for less than 2*s*. one can now buy a share in the eighty years' research, toil and experience which have gone into bringing the filament lamp to its present state of perfection, *and* get a modern 60-watt lamp guaranteed to last 1,000 hours thrown into the bargain. It must be even more difficult for the layman to believe that for one unit of electricity costing about 2*d*. to 3*d*. the electricity supply people will provide the energy to burn such a 60-watt lamp for more than sixteen hours.

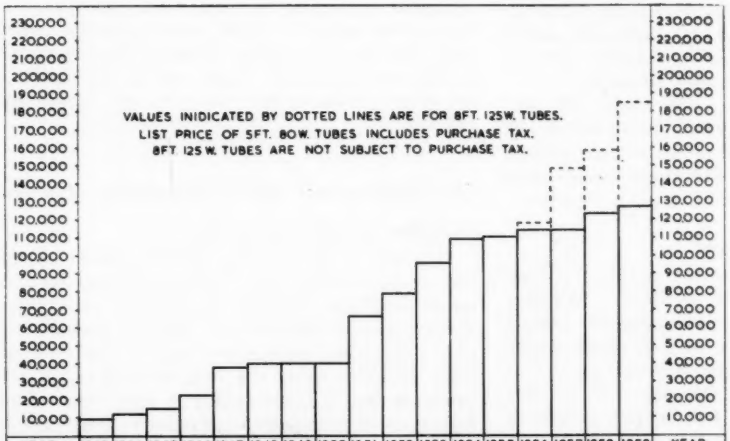
(3.2) Gaseous discharge lamps

Between the wars, the mercury and sodium vapour lamps were developed. In addition to providing excellent high-mounted light sources in industrial installations, these lamps make life safer in our streets at night for the pedestrians and the motorist. The industry, always anxious to protect the interests of the ladies, continues successfully towards correcting the greenish colour of the one and justifying the yellowish hue of the other.

Later research gives us: (1) The colour-corrected mercury fluorescent lamp for industry and public lighting which develops about 40 lumens per watt. (2) The linear sodium lamp now coming into use for street lighting and offering the high conversion of 100 lumens per watt of electrical energy, which gives four times as much light for the same running cost as obtainable twenty-five years ago and ten times what we could get fifty years ago.

(3.3) Fluorescent tubes

It has been in the last twenty years, however, since the advent of the now familiar fluorescent tube, that lamp designers and manufacturers have made their greatest strides for commerce and industry. It was the catastrophe of the 1939 World War, with its demand for output at any cost and full-scale day and night production, that jostled the lighting industry into completing development


VALUES INDICATED BY DOTTED LINES ARE FOR 8FT. 125W. TUBES.
LIST PRICE OF 5FT. 80W. TUBES INCLUDES PURCHASE TAX.
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YEAR		1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	YEAR
LIGHT OUTPUT (LUMENS)	5ft. 80W.	2160	2160	2150	2160	3040	3040	3040	3040	3040	3640	3680	4000	4160	4160	4320	4640	4640	5ft. 80W. LIGHT OUTPUT
	8ft. 125W.														7125	7125	7625	7750	8ft. 125W. (LUMENS)
LIFE IN HOURS		2000	2000	2000	3000	3000	3000	3000	3000	5000	5000	5000	5000	5000	5000	5000	5000	5000	LIFE IN HOURS
LIST PRICE	5ft. 80W.	36/6	30/-	24/-	24/-	20/-	19/-	19/-	19/-	19/-	16/-	16/-	15/2½	15/8	15/8	15/8	15/8	15/3	5ft. 80W. LIST PRICE
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LUMEN HRS. PER PENNY	5ft. 80W.	9,850	12,000	15,000	22,500	38,000	40,000	40,000	40,000	66,650	78,000	95,800	109,600	110,600	114,900	114,900	123,000	127,000	5ft. 80W. LUMEN HRS. PER PENNY
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Fig. 1. *Increase in lumen hours per penny from fluorescent tubes since* 1943

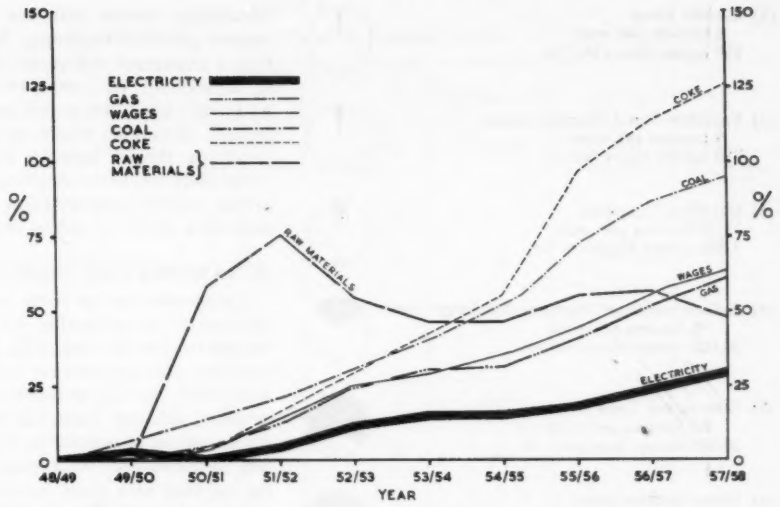

Fig. 2. Percentage increase in production cost factors from 1948 *to* 1958.

of this new form of lighting and making the fluorescent tubes available to establishments concerned in boosting the war effort. Since then further research has continued, together with improvements in manufacturing techniques, and we now have a fluorescent tube in size and colour to suit every requirement of home and factory, office or shop, and even the milking parlour on the modern farm. The makers specify a guaranteed life of at least 5,000 hours with a light output of about 60 lumens per watt, which is three or four times that of the modern tungsten incandescent lamp.

Increasing demand and improved techniques in manufacture have enabled prices of the fluorescent lamp to be steadily reduced so that the user obtains no less than 185,000 lumen-hours for one penny invested in the cost of the tube compared with less than 10,000 in 1943. This phenomenal example of production and marketing achievement is well illustrated in Fig. 1.

It will be noted that the price of an 80-watt tube plus purchase tax has been lowered to less than half its original price and that in four years the price of the 125-watt tubes (which do not carry purchase tax) has been brought down by 30 per cent. The life span of these tubes has been more than doubled from 2,000 hours in 1943 to 5,000 hours in 1959.

(3.4) Electricity supply

Progress in the lighting industry has been matched by the electricity supply side. In the generating stations we can now extract 24 per cent more energy from a pound of coal than we could twenty years ago. Over the last ten years, efficiencies in the transmission and distribution of electrical energy have also been raised considerably. As a result, over a period when so many of the cost factors which affect production have shown rises like 61 per cent for gas, 63 per cent for wages and 48 per cent for raw materials, 126 per cent for coke and 92 per cent for coal, the price of electricity has risen by only 30 per cent. The trends in production costs are shown in Fig. 2.

In managing to keep down the average price of one unit of electricity over the country as a whole to 1·32*d*. for industrial use and 2·1*d*. for commercial use, the electricity supply people deserve full credit. This is especially so when we realize what we can do with one unit which, through a reasonably efficient machine, will produce no less than 60 h.p. for one minute.

(3.5) The cost of lighting

Taking into account the improvement in efficiency in providing electricity for lighting and of utilizing it at the light source and allowing for the reduction in the manufacturer's price of present-day lamps, the cost of artificial light today is only about one-fortieth of what it was thirty years ago.

Fig. 3 illustrates the phenomenal progress that has been made in the utilization of electricity for lighting purposes since the carbon lamp came into its own in 1879.

(3.6) Inclusive cost

When all the fixed and running charges are taken into account, the complete annual cost of a lighting

years, the principle and the basic components of this form of lamp, consisting of the sealed bulb, the filament and the cap, have not been changed.

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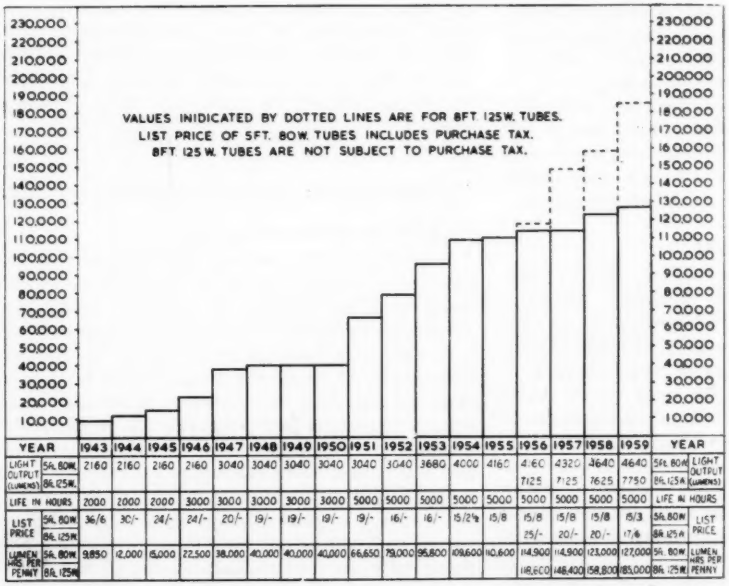

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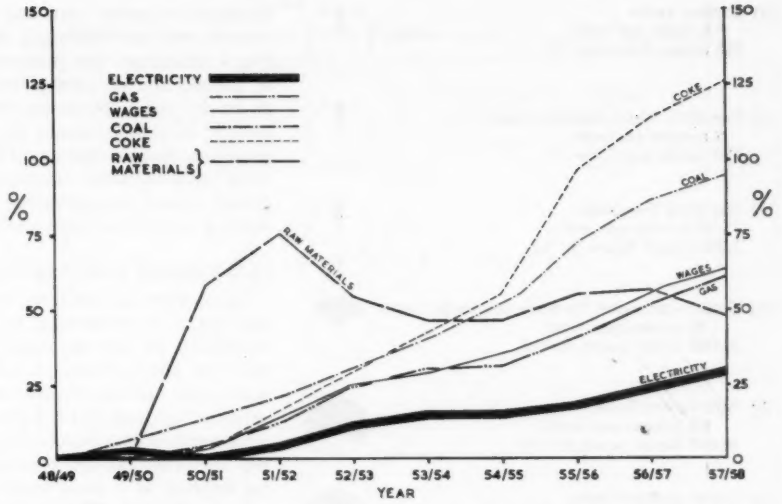

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(3.4) Electricity supply

Progress in the lighting industry has been matched by the electricity supply side. In the generating stations we can now extract 24 per cent more energy from a pound of coal than we could twenty years ago. Over the last ten years, efficiencies in the transmission and distribution of electrical energy have also been raised considerably. As a result, over a period when so many of the cost factors which affect production have shown rises like 61 per cent for gas, 63 per cent for wages and 48 per cent for raw materials, 126 per cent for coke and 92 per cent for coal, the price of electricity has risen by only 30 per cent. The trends in production costs are shown in Fig. 2.

In managing to keep down the average price of one unit of electricity over the country as a whole to 1·32*d.* for industrial use and 2·1*d.* for commercial use, the electricity supply people deserve full credit. This is especially so when we realize what we can do with one unit which, through a reasonably efficient machine, will produce no less than 60 h.p. for one minute.

(3.5) The cost of lighting

Taking into account the improvement in efficiency in providing electricity for lighting and of utilizing it at the light source and allowing for the reduction in the manufacturer's price of present-day lamps, the cost of artificial light today is only about one-fortieth of what it was thirty years ago.

Fig. 3 illustrates the phenomenal progress that has been made in the utilization of electricity for lighting purposes since the carbon lamp came into its own in 1879.

(3.6) Inclusive cost

When all the fixed and running charges are taken into account, the complete annual cost of a lighting

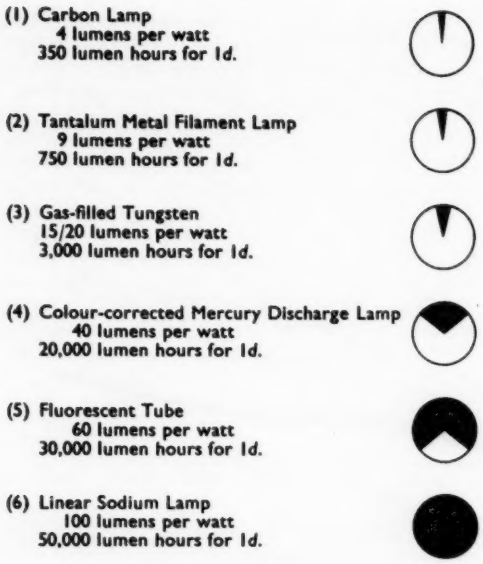

(1) Carbon Lamp
4 lumens per watt
350 lumen hours for 1d.
(2) Tantalum Metal Filament Lamp
9 lumens per watt
750 lumen hours for 1d.
(3) Gas-filled Tungsten
15/20 lumens per watt
3,000 lumen hours for 1d.
(4) Colour-corrected Mercury Discharge Lamp
40 lumens per watt
20,000 lumen hours for 1d.
(5) Fluorescent Tube
60 lumens per watt
30,000 lumen hours for 1d.
(6) Linear Sodium Lamp
100 lumens per watt
50,000 lumen hours for 1d.

Fig. 3. Improvements in lamp efficiency and cost of lighting. Allowance is made for the change in price of electricity and though 100 lm/w is shown as a full circle greater efficiencies may be expected in the future.

installation varies with the type of lighting employed and the mounting height of the fittings. Fig. 4 illustrates this point in respect of a factory of 20,000 sq. ft. (200 × 100) lighted to provide 20 lm/ft.² for 1,000 hours per annum. The figures (which, of course, would be different for factories requiring longer lighting hours for say two or three shift working) emphasize the importance of giving expert consideration to all factors before making a choice of one or other form of lighting.

(3.7) Lighting costs/wages costs

Employees can do little without effective lighting and it is interesting to compare the cost of electricity for lighting with the cost of wages. In practice, the comparison varies with the type of work done and the number of hours worked under artificial lighting. Table 1 gives comparative figures for a number of industries; it includes two windowless factories and on average the electricity used for lighting at a good level of illumination works out at about 1·37 per cent of the wages paid during the lighting hours.

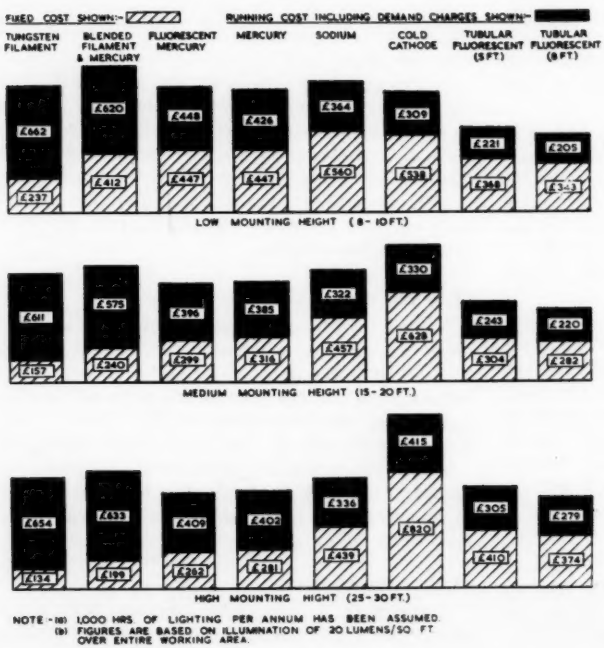


Fig. 4. Total annual lighting cost for a 20,000 sq. ft. factory for different light sources and different mounting heights.

Table 1
Wages costs compared with lighting costs

Industry	Weekly Average		Lighting as a percentage of wages	Lighting costs per £1,000 wages	Illumination (lm/ft.²)
	Wages when artificial light is used	Lighting running costs			
	£	£ s. d.		£ s. d.	
Mineral water manufacture and bottling	367	6 5 0	1·70	17 0 0	20
Chemical production	600	4 17 0	0·81	8 2 0	30
Electronic equipment assembly ...	2,000	4 17 0	0·24	2 8 0	50
Shoe manufacture	150	1 10 0	1·00	10 0 0	15
Light engineering	2,670	38 2 0	1·43	14 5 0	15
Furniture manufacture	90	1 5 0	1·35	13 9 0	16
Dairy produce factory	147	2 10 0	1·70	17 0 0	18
Printing works	131	3 0 0	2·29	22 18 0	25
Heavy engineering	5,960	173 0 0	2·90	29 0 0	17
Large office	1,710	5 15 0	0·34	3 7 0	30
				137 9 0	

Average lighting costs as a percentage of wages is 1.37 per cent.

Using fluorescent lighting in a factory of 20,000 sq. ft. it is possible adequately (20 lm/ft.²) to light the working plane of 100 sq. ft. of floor area for 1,000 hours—a fair annual average where there is a representative share of natural light—for about £2 10*s.* 0*d.* This is about 1*s.* 0*d.* per week, or just over ½*d.* per working hour during lighting hours. This assessment includes all the capital charges of fittings and installation, the electricity consumed, replacement of lamps and maintenance. It is based on a realistic coefficient of utilization taking into account the appropriate reflection factors of walls, ceiling and floors. Under the conditions stated, if we take 100 sq. ft. of floor space as a fair allowance for one operative earning £10 per week, the inclusive lighting component of the factory works out at about 2 per cent of the labour costs during the hours of artificial lighting. Looked at another way, the cost in time alone of a ten-minute morning and afternoon tea break is over six times the total cost of providing a really good standard of artificial lighting.

(4) The Case for Better Lighting

We can accept that the lighting installation is a form of investment. As such it is a tool of production management and should rank in this respect equally with new plant and machinery and be kept under continuous review, wisely depreciated and renewed or refurbished regularly to keep pace with new developments. There is a tendency, particularly among the managements of smaller establishments, to dismiss the cost of lighting as though it were another irksome and inescapable form of overhead charge which, like rents, rates and insurances, have to be kept constant at minimum levels.

Far too often the electricity units consumed by lighting are absorbed in the main electricity account, and being out of sight are out of mind. As a result it is common to find managements unaware of what their lighting means in terms of money. This leaves them without an economic incentive for investigating their return on lighting expenditure and seeking means of obtaining better value for money by wisely deploying lumens to raise

production efficiency and improve working conditions. This leads to the consideration of separate metering of lighting circuits, especially in factories, which is not always a simple matter on existing installations where trunked lighting cables also supply other services. Ways and means can usually be found, however, and I should like to see the wiring, at least in all new installations, planned to enable metering or sub-metering of the lighting circuits. Electric meters should really be part of the working equipment of a factory engineer and they are not expensive to buy. Alternatively, Electricity Boards, seeking further information about the lighting load, are usually amenable to approach by the consumer for loan or hire of metering equipment. While it is true that lighting consumption can be estimated by multiplying the watts installed by the lighting hours, the method is haphazard and not sufficiently accurate to produce a fair and realistic appraisal.

We must be most careful not to form any wrong ideas that good and improved lighting is merely a matter of fitting bigger lamps to give increased illumination. Certainly the level of illumination has considerable bearing, but comfort and general agreeability in seeing are of first importance and, therefore, choice of fittings, the placing of lights to avoid glare and to make the best of shadows and especially the full use of colour, must be carefully considered.

(4.1) Production and output

Eighty per cent of all actions are said to be visually controlled, i.e. they consist first of seeing and then of reacting to what is seen. Obviously, therefore, good light is essential to quicker and better work or, in more appropriate words for my subject, to high quantity and quality of production. Unpleasant working conditions, associated with gloom of badly lit premises, are bound to reflect in reduced working speeds and poor work.

Good lighting also reduces eyestrain and the consequent fatigue which, if allowed to persist, cannot fail to cause accidents and illness and generally to have a bad effect on output and work standards. In referring to eyestrain, it is interesting, and perhaps significant, to note that in 1958 33 per cent of the young males and 17 per cent of the young females classified as unfit for employment by medical examination under the Factory Acts were rejected because of refractive or other eye troubles. This could mean that the standard of eyesight in youngsters is not so good as in earlier days. If such is the case, it would pay all employers to provide really good lighting for the jobs they expect these young people to perform.

There are other ways in which good lighting contributes to the profitability of an establishment. These include: minimizing operative errors, facilitating inspections and reducing spoilage; 'bringing out' the dirt, creating a clean and healthy environment which encourages recruitment—a valuable asset in times of full employment; reducing the handicap imposed by lack of skill at bench or machine and thus making the employer less dependent on the experienced worker; keeping up the working efficiency of the older operatives when their eyes begin inevitably to suffer the ravages of age.

These points apply in varying degrees to any industry, business, profession or activity where work is carried out by people employed for gain in one way or another. We must be careful not to exclude the thousands of offices where better lighting has yet to find its true place.

(4.2) Trading

Special factors have to be taken into account in dealing with lighting for commerce and trading. In cases such as large stores and shops, managements and lighting engineers have the responsibility of catering for the comparatively short and changing interests of the public as well as of employees. They must, in addition to providing good levels of illumination, have regard to colour matching, decor and special arresting features as well as to comfort and agreeability. There is no doubt that lighting planned in this way will stimulate the purchasing inclinations of the customer and the selling enthusiasm of the sales staff, which go together in increasing the profitability of the business.

(5) Proof

(5.1) Shortage of information

I find that much of what I have said earlier about the economic advantages of a good standard of lighting is taken so much for granted in the lighting industry that very little has been done to employ what I call case histories to bring the facts and proof to the attention of the users.

There are, of course, thousands of users among the large and more progressive firms who well know the economic value of good lighting and employ it in full, but for one reason or another the 'trade' and the 'customer', with true British conservatism, have certainly not gone out of their way to put their achievements on record. This really takes us all to task.

Lamp and fittings manufacturers need data obtained from experience and require this information to help them sell their products. The lighting engin-

Name and address of firm .....
Type of business ... ...
.....

Name and address of lighting engineers ... .
.....

Name and address of observer... ... ...

Test Data

Period of test ... ...
Original factory output ... .
Final factory output ... .
% change in output ... .
Original rejects ... ...
Final rejects ... ...
% change in rejects ... .

Remarks

Reaction of staff, etc.

(This space to be at least half a page.)

	Original Installation	*Final Installation*
Floor area	.....	.....
Number of workers	.....	.....
Capital cost of installation...	.....	.....
Number of lighting fittings...	.....	.....
Type of lighting fittings ...	.....	.....
Amount of local lighting ...	.....	.....
General level of illumination	.....	.....
Local level of illumination...	.....	.....
Total wattage of installation	.....	.....
Units of electricity consumed	.....	.....
(*a*) from.....to.....	(*a*).....	
(*b*) from.....to.....		(*b*).....
Man hours for maintenance and cleaning fittings ...	.....	.....
Colour of ceiling	.....	.....
Colour of walls	.....	.....
Colour of floor	.....	.....
Colour of overhead services	.....	.....
Colour of machinery ...	.....	.....
Colour of benches	.....	.....
Observer's Reaction		
Feeling of glare	.....	.....
	.....	.....
General impression	.....	.....
	.....	.....
	.....	.....
	.....	.....
	.....	.....

Fig. 5. Suggested standard survey form of report for registering conditions before and after lighting installations have been improved.

eers naturally are always keen to see published proof about the value of their work. Electricity Boards can use the knowledge of their efforts to widen and improve their service to consumers. Prospective users wish to know beforehand what they stand to gain by improved lighting and afterwards what they have achieved by so doing. In short, we all stand to gain by helping to place up-to-date evidence of the way lighting aids production on accessible record.

What is needed in my view is a standard form of report for registering conditions before and after lighting installations have been improved and showing the economic value of the changeover. Completion of the form would be a combined operation by the installation engineer, the Electricity Board and the user. Summarizing the information in the reports, putting it into suitable form and publishing it to all interested parties, might well be a task for the British Lighting Council. The type of form I have in mind is shown in Fig. 5.

(5.2) Case histories

Table 2 gives some of the case histories to which I have already referred. These examples must, of course, be interpreted with care. This is not because they exaggerate, but because the refurbishing of a lighting installation is often arranged to coincide with other changes such as new layouts and sometimes new machines. Also, new decoration normally takes place at the same time, which is as it should be, since the full benefits of improved illumination cannot be secured without wise use of colour.

There are many other examples where, although I am not giving detailed figures, I know the managements are completely satisfied that improved lighting has directly or indirectly given one or more of the advantages mentioned earlier. Brief details of these are as follows:

Case 1

To test the theory that better lighting of shops encourages bigger buying, a large chain chemists refurbished the lighting installations in fourteen shops in a Northern territory and increased the illumination by 10 lm/ft.^{2} Turnover increased by 20 per cent.

Case 2

The 30-year-old lighting in a drapery store was replaced completely by a new fluorescent system. The management state that the turnover rose by 19 per cent within six months; in their opinion this was due entirely to the brighter and more inviting appearance of the shop.

Case 3

A tile manufacturer, experiencing difficulties with selecting matching coloured tiles for fireplaces, installed a new system of local lighting employing colour-blended fluorescent tubes to give 140 lm/ft.^{2} over the inspection benches. A consequent initial increase in rejects led eventually to an improved kiln design and a tightening up of the production processes. The outcome was a better end product, with tile faults virtually eliminated.

Case 4

An improvement in illumination from 2 to 10 lm/ft.^{2} in a foundry so improved the conditions for mould pouring and inspection, that the saving in rejects covered the cost of the new lighting installation in the first year.

Case 5

Until quite recently it was accepted that plain paper overhauling could be carried out only in daylight, necessitating cessation of the work before dusk. A special lighting fitting containing 80-watt colour matching fluorescent tubes was designed and installed and proved to be even better for the purpose than natural light. The new lighting system enables overhauling to be carried out at any time and has brought about a 10 per cent increase in the speed of the operation.

Case 6

A large steel tube foundry reports that improved lighting using mercury discharge lamps enables hair cracks in the castings to be detected with far more speed and certainty than previously and that the quality of despatched products has risen sharply.

Three other cases came to my notice when I had almost completed the paper. In post office sorting a doubling of the lighting level from 3 to 6 lm/ft.^{2} gave an increased output of 20 per cent. Similarly a lighting improvement from 3 to 9 lm/ft.^{2} gave a 17 per cent boost to output in a wire drawing shop and production of roller bearings went up by 12½ per cent after the lighting had been stepped up from 5 to 20 lm/ft.^{2}

In horticulture, supplementary lighting for tomato and cucumber seedlings is enabling the British grower not only to increase his output, but to catch the early market when prices are high. The use of tungsten lighting to lengthen the day is providing chrysanthemum blooms for any time of the year. On one holding, off-peak lighting is giving an all-the-year round production of 25 million chrysanthemum cuttings annually for new markets at home and overseas. A hundred or more cuttings can be provided for one unit of electricity.

Increased output comes also from using artificial

Table 2

Advantages gained from good lighting

User	Class of work	Lumens per sq. ft.		Results				Other Comments	General Observations
		Original	New	Increase in Output (per cent)	Decrease in Rejects (per cent)	Decrease in Absenteeism (per cent)	Decrease in Accidents or Illness (per cent)		
Douglas Aircraft (USA)	Electrical component assembly (value $100 to $10,000 each)	N.A.	400		89 (from 28 to 3 a day saving $2,500 daily)	100	100 (migraine headaches)	Major increase in employee morale	
Helipot Corpn. (USA)	Assembly small metal parts	N.A.	200	16	28	—	58 (accidents)	Installation cost paid off by savings in 8 months	Results determined by independent auditor
The Erikson Tool Company (USA)		N.A.	200 (general) 300 (special)	10	20	—	50 (accidents)	Installation paid off by savings in 3 months	
John Wilson & Sons Ltd., Lothersdale, near Keighley, Yorks.	Rayon weaving	7	20-30	10·1	58	—	—	Increase in employee morale	Annual production increase equivalent to nearly 8 weeks' work at original rate

N.A. Not available

Table 3

Saving in changeover

Installation	Original Installation (Tungsten)			New Installation (Mercury Fluorescent)			Cost of Conversion	Annual saving	Capital Recovery Period Years	Level of Illumination
	Loading kW	Annual running cost	Annual maintenance and depreciation	Loading kW	Annual running cost	Annual maintenance and depreciation				
A	550	£8,720	£1,851	155	£2,475	£851	£3,706	£7,245	0·51	Up to standard
B	96	£2,840	£378*	57·6	£1,730	£564†	£2,330	£924	2·52	Increased from 3·5 lm/sq. ft. to 12 lm/sq. ft.
C	1,527	£29,249	£6,983	785	£13,674	£6,916	£26,901	£15,642	18·4	Maintained

* This figure excludes depreciation.

† This figure includes depreciation on additional capital equipment.

light in inexpensive unglazed buildings as distinct from costly greenhouses. Millions of flowers are now being produced annually from flowering bulbs and the plants never see daylight. Varieties of forced tulip and daffodil bulbs produce blooms out of season in three weeks or less from being planted out in the lighted building. Not only are the heating losses in the unglazed buildings substantially less than in greenhouses, but the use of artificial light permits much greater growing capacity because the bulbs can be tiered in trays.

For some years extended artificial lighting has been successfully employed in standard poultry houses to encourage fully grown hens to lay more eggs. Windowless buildings are now being used and by control of the lighting to vary the day length during the early life of the birds, they can be persuaded to grow faster and commence laying eggs of a good marketable size and weight. Tests to date show a profit increase of 7*s*. per head of stock over the older methods.

(5.3) Saving in changeover

When thinking of the changes necessary to existing lighting installations I was reminded of the Brittania Hangars at the Bristol Aircraft Company (Table 3, Installation A). When the original installations were completed, the standard of illumination provided by combined 400-watt high mounted mercury discharge lamps and 1,500-watt tungsten filament lamps was well above average. With the object of reducing running and maintenance costs changes were made. A number of the high-mounted tungsten 1,500-watt lamps installed originally to offset the poor colour effect of the mercury lamps were replaced by 400-watt colour corrected mercury discharge lamps. Records were kept and it is now possible to show other prospective users of this form of high bay lighting, that the management recovered the total cost of the changeover, amounting to about £3,700, in six months out of reduced costs of electricity and lamp replacements.

Another rather similar example (Table 3, Installation B) is that of a steel pressing factory in the south-west where a change to colour corrected mercury lighting from incandescent lamps cost £2,330. The level of illumination was increased from 3·5 to 12 lm/ft.^{2} and the inclusive annual running costs were reduced by £924 per annum, with the result that the changeover will be paid for out of savings in two and a half years.

Installation C (Table 3) refers to a large motor factory where the cost of the new colour corrected mercury installation will be recovered in less than two years. The saving in running costs and maintenance will work out to something like £15,000 per annum on a capital cost of £27,000. This really is big money and cases of this nature deserve to be recorded.

You may be wondering how, as an electricity supply engineer who lives by selling electricity, I can justify recommending conversions to modern lighting which give the same illumination for vastly reduced consumptions of electricity. Of course, we like to sell plenty of current, especially at the right time of day and at night, but we are also as much concerned to give first-class service to our consumers. Fortunately, in practice it so happens that a user who gets good results from one well-planned lighting job goes on improving his lighting and other electricity services. Eventually he becomes a bigger and better, and certainly more satisfied, consumer.

Figures are not available in this country, but in Holland the national use of electricity for lighting is growing at a rate equivalent to that for electric power used for other purposes. This, of course, indicates that the higher efficiencies in modern sources of lighting are indeed being converted into 'candles' instead of 'pennies'.

The exact proportion of electricity consumed for lighting in industry in Great Britain is not known. It is thought to be somewhere between five and ten per cent. For shops and quite large modern stores some recent investigations show that the electricity consumed for lighting purposes is about 60 per cent of the total used, which emphasizes the importance attached to artificial lighting for selling.

(6) Illumination Codes

Some statutory welfare levels for general industrial lighting have been laid down by the Factories (Standard of Lighting) Regulations, S.R. & O. No. 94, 1941, but they are designed to do no more than ensure a reasonable measure of safety and to keep glare down to an acceptable limit.

Recommended illumination values for different industrial and commercial occupations and tasks have been drawn up and published by the Society in the IES Code. The latest edition, issued in 1955, serves a most valuable purpose as a guide to all who are concerned with or who contemplate new or revitalized lighting installations.

Codes of practice, to serve their full purpose, need constant revision in the light of progress and development in other spheres. If one compares the British Code with those of other countries, notably America, one finds that for many uses our present recommended values are very much on the low side.

There are, of course, always people who, once a code is issued, will stick rigidly to it in practice merely because it is a code. I have always preferred to look upon the IES Code as suggesting minimum values above which there must be unlimited freedom for the lighting engineer and, of course, the user, to install lighting which above all provides a means of seeing and working easily in maximum comfort and agreeability. I certainly should not like it to be mistakenly construed from my remarks that the place of lighting in our business rests solely on its direct profit-making ability. We must also light for the joy and pleasure that good lighting gives and the profound influence it can exert on our outlook at work and at leisure.

(7) The Lighting Engineer

(7.1) The place of the lighting engineer

In this country by far the greatest number of lighting engineers will be found in the ranks of the manufacturers of lamps and fittings. Most of these engineers, of necessity and as part of their service to their clients, combine technical and advisory work with selling. Only the larger business concerns employ their own lighting engineers, usually attached to the staff of the chief engineer, works engineer or the firm's architect. In the majority of establishments, particularly the smaller ones, lighting is just another job for the civil, mechanical or electrical engineering staff.

There is much more in the job of the skilled lighting engineer than meets the eye. Many difficulties associated with maintenance of installations, for instance, can be met by wise planning and siting and the design and choice of fittings, while careful study of cleaning and lamp replacement problems always pays handsome dividends.

In one large factory building with which I was connected, a decision to replace all lamps in groups after a predetermined number of burning hours instead of replacing lamps individually as and when they failed, brought about a reduction in lamp replacement costs from £1,250 to £350—a saving of about £900 per annum. This saving was effected notwithstanding that the group replacement work was done over week-ends and earned double pay for the maintenance crew. Originally, sporadic individual replacement of burnt-out lamps required the electricians to be frequently and wastefully moving to and from the stores and for every replacement of one or two lamps, work of machines and operatives was interrupted.

I hope that by emphasizing the economic importance of lighting we can attract more young engineers to this interesting profession for employment by the users rather than the sellers of lighting. For this to happen, managements must recognize the value of having an independent lighting engineer at their command. More training courses will be required and there needs to be some raising of the professional status of lighting engineers commensurate with the effective contribution they have to make to productive efficiency. Most Electricity Boards could well do with lighting specialists, particularly to advise smaller users.

(7.2) Consultants

There seems to be considerable scope and need for free-lance consultants in lighting engineering, men with whom architects will not be too proud to co-operate in the early stages of projects and on whom managements, especially when contemplating new buildings and factories, can call for independent advice.

(7.3) Integration

I must add my weight to the view, so often and more adequately expressed, that lighting must be pre-planned as part of the basic design of all new buildings small and large, so that the associated questions such as wiring, light source placings, ease of maintenance, use of colour and the degree to which artificial light is to supplement natural daylight can be dealt with as one problem. I hope the days have long passed when lighting is treated as a mere accessory to be incorporated (or shall I say squeezed) into a predesigned and often prebuilt structure. Fig. 6 shows lighting units mounted immediately beneath a cat-walk thus facilitating maintenance, and Fig. 7 indicates a system where the lighting units are mounted on trunking and can be easily moved longitudinally making possible an increase or decrease in the lighting intensity in a matter of minutes.

(8) Colour in Lighting

Good lighting and judicious colouring go together. Each is dependent upon the other to a far greater extent than is generally realized. In the factory, colour of machines, colour of the surrounding walls, floors, roofs or ceilings and colour at the working bench, if employed in pleasant combination with artificial light, can be vital factors in controlling fatigue. In this way greater operational accuracy and speed can be achieved by promoting the interest of workers in their tasks and minor accidents and occupational illnesses, which collectively build up costly absenteeism, can be reduced. This is another way of saying that the skilled lighting specialist needs to have an artistic understanding as well as a good lighting engineering knowledge.

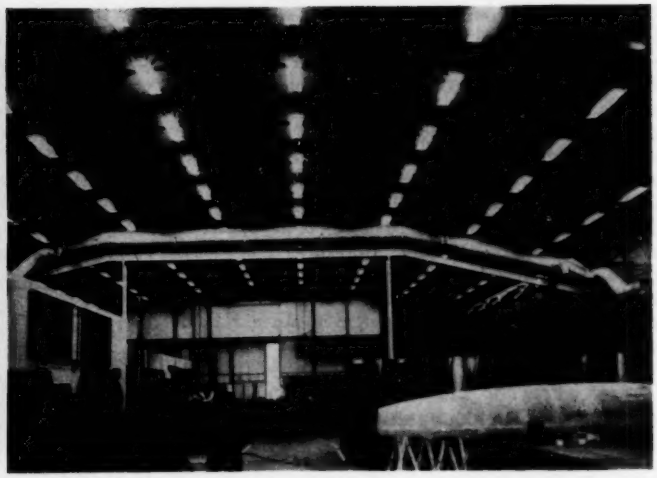


Fig. 6 (*left*). *Lighting units mounted beneath a cat-walk to facilitate maintenance.* *Fig.* 7 (*right*). *Installation of lighting units on trunking.*

On the commercial side, in the world of store lighting, it is said that potential customers, like moths, are attracted to light. By and large a good lighting engineer with an artistic flair, using planned design and a good balance of colour, can virtually predetermine the customers' reactions, control their movement within the store and certainly save them the trouble these days of walking to the door of the windowless shops for daylight to test colours of their lipsticks!

(9) The Future

(9.1) Competition

Among the recognized ways of facing the growing problem of foreign competition, increased productivity at home must rank fairly high, and I have shown how improved lighting and all that it implies can help to this end. In existing factories, offices, stores and other establishments, it is reasonably simple and inexpensive for managements to check and improve lighting installations which fall below the recommended standards of today. In setting sights for the future, it is the new factory, store and office to which we, and our architects, must direct our attention.

(9.2) The cost of daylight

Ever since the building of King Solomon's temple it has been one of the basic aims of architecture to provide interiors of buildings with the maximum amount of natural light and to use artificial lighting only as a supplement. It is fair, I think, to say that we are beginning to recognize, and here and there to accept, that daylight is far from being a necessity in successful building design. Daylight has in fact been described as an expensive luxury.

While we must keep our sense of proportion in this matter, we must have regard for the way in which glazing for daylight both directly and indirectly influences production costs. By and large the greater the area of glass, the higher the cost of construction. The significance of this point is brought out by Hopkinson and Longmore in their recent paper. They show that but for the wish to give adequate daytime penetration of natural light into six new laboratory buildings in a technical college, the ceiling heights could be reduced from 14 ft. to 10 ft. so effecting a reduction of £825 in the annual capital charges on construction costs. The increased cost of extra artificial lighting necessary to replace the excluded daylight would amount to about £129, so showing a net annual saving of some £700.

This, I believe, may well be an indication of future trends. If we take into account the reduced heat losses and lower maintenance costs due to a smaller area of glazing, the saving would be much greater.

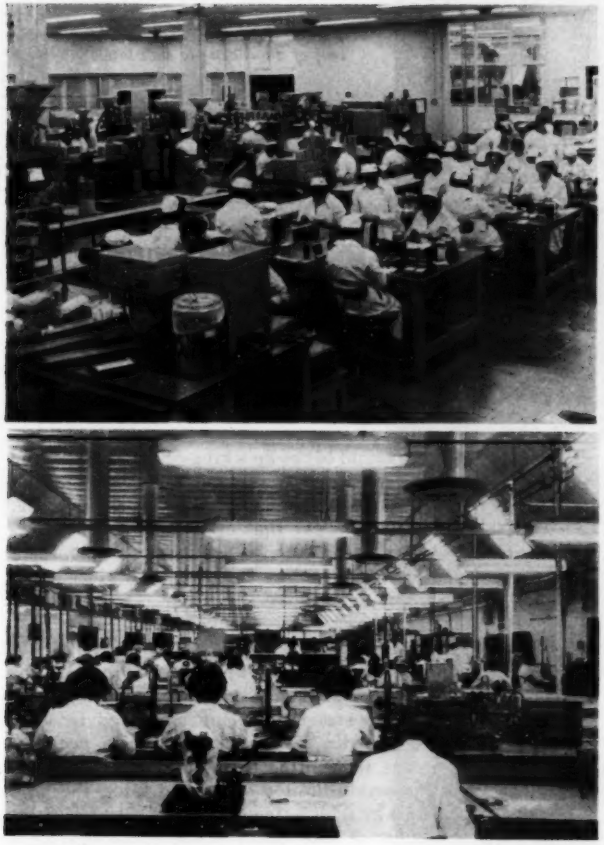


Fig. 8. The interiors of two windowless factories. Note the false skylights in the lower picture.

(9.3) The windowless factory

The demand for lower capital costs will perhaps take us even further towards the windowless factory. There are already some such buildings in use here, and in other countries, for handling work of a special nature requiring temperature and humidity control combined with super-cleanliness.

In addition to savings on construction and maintenance, other factors which may well give industrialists cause to favour the idea of windowless type factories are:

(*a*) *Legislation*

Heat losses in new industrial buildings and extensions now have to be kept to a statutory minimum laid down by the Thermal Insulation Act (Industrial Buildings) 1957, which came into force on January 1, 1959. Although the Regulations lay down 'U' values only for the unglazed sections of roofs, the aim of the government in trying to conserve fuel is quite clear. Glass, however, is notorious for its property of wastefully conducting expensively produced heat out of a building in the winter and of letting in free uncomfortable and unnecessary heat during the summer. Unquestionably, the new legislation will be bound to exert some influence on future building design. Equally obviously, the less glass employed to save heat the greater the need for well-planned and adequate artificial lighting.

(*b*) *Combined heating and lighting*

All forms of lighting generate a certain amount of heat. At least one of our progressive engineering firms is using this heat to supplement, on a thermostatically controlled basis, the main space heating of the factory. This, like the heat pump (which has blown cold as well as hot over the years) is a development that surely will one day become a pacemaker in the race for reduced running costs.

Fig. 9. Example of car parking on the roof of a building to save land.

(*c*) *Space limitation*

Here we have social problems, one solution to which may also be found in progressively reducing roof and side glass in new buildings, especially on trading estates outside the city walls. Land is becoming increasingly valuable and more expensive to purchase or to rent. Should this situation not lead us to think in terms of abandoning roof glazing in single-storey buildings on new trading estates or fringe industrial and commercial building sites in favour of reinforced concrete roofs designed for use as car parks? From here it would be but a short step, having regard to the saving attributable to lower ceiling heights with less side glazing to go still further and secure all the other advantages of glass-free buildings relying entirely on artificial lighting.

(*d*) *Working conditions*

The idea of working without daylight will not be popular—notwithstanding that we already spend a very large part of our lives in these conditions and that windows for letting in daylight have long since virtually disappeared from the large store and shop scene without causing any labour problems. At first, objections by operatives—largely psychological—would arise from an inherent fear of being shut away from a natural environment, but they are surmountable by such means as dummy view windows and exits and entrances designed to avoid abrupt changes in light for people moving into and from the building. In bright summer months the implications of moving into or from a windowless factory, however well lit and agreeable, are not difficult to imagine. In the dark months, however, the situation is different, and I have been told of operatives in windowless factories who literally dread the sound of the knocking-off whistle inviting them to emerge into the fog and smoke of an industrial area at five o'clock on a winter evening. It seems fairly clear that eventually the windowless factory will become as common to our children as the standard factory building with glazed roof and sides is to us today.

(9.4) Animation

As levels of artificial illumination increase, as indeed they must even if they do not reach the extremely high standards being employed in some parts of America, so is there created a need for 'movement in lighting' especially where natural light is severely limited or cut out altogether and is replaced by a high steady value of artificial light. The absence of 'movement' is not desirable since it emphasizes the exclusion of natural daylight and is inclined to produce some degree of boredom.

Just as I predict, therefore, a swing towards less glass and more artificial lighting, so do I foresee considerable development and practical use of equipment for providing automatic changes of artificial illumination and of colour for the purpose of simulating the conditions produced by daylight penetration and relieving the monotony of working in a high and constant level of artificial light. There is nothing strikingly new in this. In the theatre 'picture painting by light', as it has been most suitably named, has been used and perfected over the years.

(9.5) Enlightenment

In the future, quite apart from managements' outlook and needs, operatives will themselves press for better light and colour. Fewer and fewer workers in these days go home to poor, dimly lit homes. In

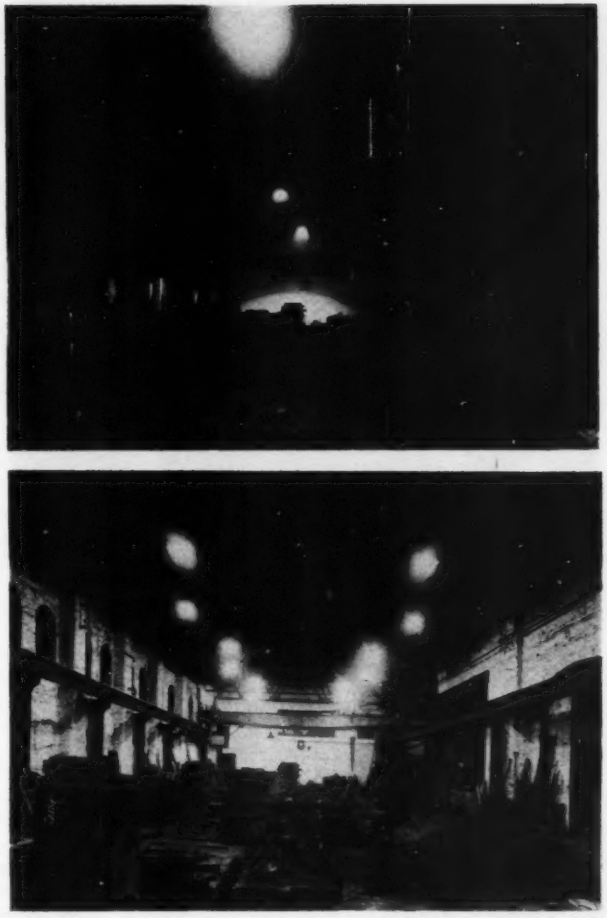


Fig. 10. *A specialist foundry before and after relighting.*

fact, growing numbers are living in well-designed houses embodying the latest ideas in comfort and efficiency and as a result they are the more conscious and critical of poor environment at work. Consequently, their interest and efficiency are likely to be far more adversely impaired by unsuitable working conditions than has been the case in the past.

(9.6) Codes of Practice and lighting levels

Clearly we are moving into an era of better lighting and need not stretch our imaginations very far to suggest that when new Codes are issued they will set higher levels of illumination than those in use at present.

(9.7) Transport

No paper on the connection between productivity and light would be complete without reference to the lighting of roads and sidings. Speedy movement of raw material and finished goods between factory and docks, works and railheads, customers and stores, is essential. The time must surely come when to increase output from our factories the main trunk roads and approaches and outlets from our manufacturing towns will have to be lighted to really high standards from dusk to dawn. Money invested for this purpose would pay excellent dividends in the form of speed in movement and turn-round.

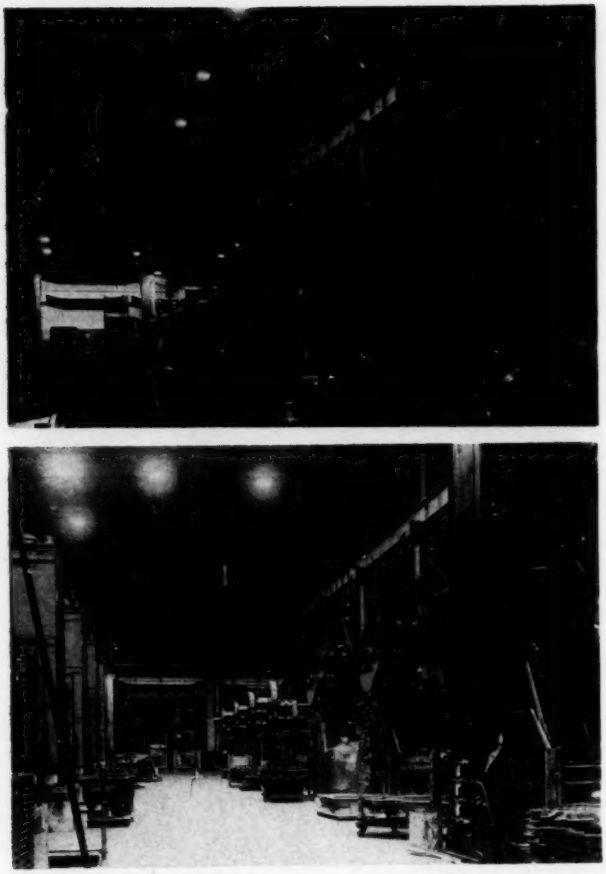


Fig. 11. *Showing the improvement in environment in a press shop after re-lighting.*

(9.8) Forms of lighting

Except for the purposes (and there are many) for which tungsten lighting is more suitable than other forms, it looks as though the increasing trend towards more fluorescent lighting in all walks of life will continue. I think we can also expect further increases in the lumens per watt obtainable from this form of lighting. We shall, I believe, be much more concerned in the future with 'lighting' and all that it implies, rather than with light sources. The movement towards higher illumination levels will probably bring about changes in the design of fittings so that the extra lumens can be converted into useful light without increasing glare. It looks as though the emphasis in fitting design will be on non-glare lighting and to this end I think there will be extended use of integrated luminous ceilings in one form or another.

We shall, I believe, see greater recognition of the value of high illumination combined with colour for inspection purposes such as detecting flaws in metal fabric, paper and other materials. There seems to be great scope for development in this field. Colour in lighting planning is clearly becoming a necessity.

(10) Conclusion

I wish to offer my sincere thanks to the many friends in the Society and industry who have supplied me with information and given technical assistance, and to all from whose works I have obtained information and guidance. In particular I must express my thanks to Mr Guscott and Mr Smart of the South Western Electricity Board, who did so much work in the preparation of the paper.

Light and Road Safety

By SIR WILLIAM GLANVILLE, C.B., C.B.E., D.Sc., M.I.C.E., F.R.S.

I should, in opening my paper this evening, first like to thank the Council of the Society for inviting me to present it: it is an honour which I greatly appreciate.

The subject of light and road safety has many important aspects. It would be possible, for example, to talk about the importance of the intensity of sunlight, of the position of the sun in relation to road users, and of a whole range of daylight variations that occur and of the effect of twilight on safety. However I have assumed that it is not on these daylight effects that I am asked to talk but rather on night visibility and in particular the influence of street and vehicle lighting. I am even narrowing down my subject further, for I propose to deal mainly with the research undertaken at the Road Research Laboratory of the Department of Scientific and Industrial Research.

The interest of the Laboratory in street and vehicle lighting has two main purposes; the first is to discover ways of improving present practice so that the risk of road accidents at night is reduced; the second is to discover the most economical means of achieving this. Where human suffering and death are being considered, questions of money may appear irrelevant, but we must remember that the most economic solution enables the greatest return in terms of the reduction of human suffering to be obtained for a given expenditure.

In tackling the problem, the work of the Laboratory up to the present has been devoted to studying the principles of street lighting, to finding a relation between the quality of street lighting and night-traffic accidents and to investigating the efficiency of vehicle headlights, rearlights and direction indicators.

The Importance of Improving Seeing at Night

Though it seems obvious that road conditions are more dangerous in the dark than in daylight, only about one-quarter of the personal-injury accidents in Great Britain occur during the hours of darkness.[1] The greater danger at night is apparently more than offset by the small flow of vehicles and pedestrians. Recently, however, there has been a tendency for night accidents to increase.

To compare night and day risks it would be helpful to know the number of accidents or casualties that would occur on any given road under any stated conditions of lighting, and the number that would occur on the same road in daylight, all other conditions remaining the same. With our present knowledge such a comparison cannot be made with any precision. Moreover, fatigue and the amount of alcohol consumed by road users, the amount and composition of traffic, differences in age and types of drivers may affect the chance of an accident occurring at night in a way that is not due directly to the darkness. Useful estimates can be made, however, of the effect of darkness by comparing accidents that occur during a period that is light with accidents during a corresponding period that is dark. Such comparable periods are provided by the gradual lengthening and shortening of the day and by the sudden change in the hours of sunrise and sunset at the beginning and end of summer-time. Pertinent information can also be obtained by analysing the relative frequencies with which various types of accident occur in darkness and in daylight. The conclusions from such investigations are that casualties as a whole are about 60 per cent more frequent in darkness than in comparable daylight conditions, and there is an even greater rise in the number of fatalities and pedestrian casualties in the hours of darkness.

Another and perhaps simpler way of illustrating the importance of improving seeing at night is to compare accident statistics for various conditions of darkness. With this in mind, the Laboratory has obtained reliable evidence of the improvements likely to result from relighting streets to modern standards, a subject that is considered later. It would be useful if similar comparisons could be made of the effect on accidents of various alternative forms of vehicle headlighting but, unfortunately, such a direct approach to the problem is not possible and no figures are available to show the effects resulting from improvements in the design and maintenance of vehicle headlamps. But it is known from an investigation carried out some years ago that poor rearlights caused about 3,400 casualties per year.[2]

The Road Illumination Problem

For ease in driving at night, the lighting system,

A lecture given in London on October 22, 1959, being one of a series of four Golden Jubilee lectures. The author is Director of Road Research, Road Research Laboratory, Department of Scientific and Industrial Research.

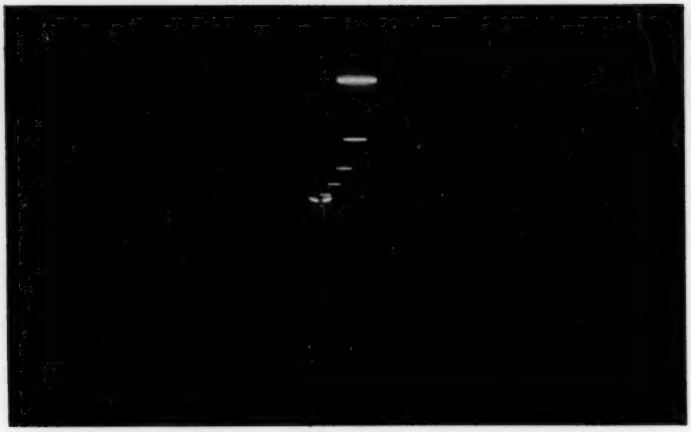


Fig. 1. In lighted streets vision is mainly by silhouette. Occasionally the silhouette is reversed in the case of a pedestrian wearing light-coloured clothing.

whether provided by street lighting or by headlamps, must do two things: it must enable objects on the road to be detected in good time, and it must enable the driver to keep his vehicle accurately in position in relation to the kerb and to other vehicles.

In satisfying these requirements, the lighting engineer is subject, for economic reasons, to a severe limitation in the amount of light that he has at his disposal. Brightness levels are therefore always low compared with daylight with the result that colour sensitivity is largely lost and so is the ability to resolve small details. It is well known that the visibility of objects then depends mainly on the existence of a brightness contrast between the object as a whole and its background. Silhouette vision occurs when the object is darker than its background, and direct vision when the object is brighter. In seeing with vehicle headlights, direct vision is the more important because the object is illuminated by the headlamps and appears bright compared with the distant, dark, road surface. Objects are also seen, but less reliably, as dark silhouettes against the road when illuminated by an oncoming vehicle's headlights. In street lighting, where the object of the lighting engineer is to make the road surface as bright as possible, the dark silhouette is by far the more important (Fig. 1).[3]

Visibility in Lighted Streets and the Effect of the Road Surface

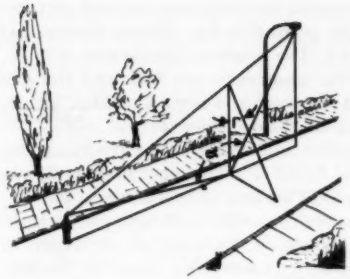
Revealing power

One of the first investigations carried out at the Road Research Laboratory on street lighting concerned revealing power, a concept developed earlier by Waldram,[4] Dunbar,[5] and Smith[6] to assess the merit of a street-lighting system. These workers have defined the revealing power of a part of the background as the percentage of possible objects which are adequately visible to a driver when seen against it. Fortunately Harris and Christie found a method of greatly simplifying the treatment of revealing power.[7] This treatment showed that the numerical values of the revealing power of an element of road surface viewed from a particular place was largely determined by two factors only, the brightness of the element and the average illumination on vertical objects in the street. This analysis enabled general conclusions to be drawn, much more easily than formerly, of the effect on revealing power of changes in the road surface or in the street-lighting installation. It showed that an increase or decrease in reflecting power of the road surface had a much greater effect on revealing power than a corresponding percentage increase or decrease in the light output of the lighting installation. This is because increasing the light output of the installation brightens both the light patch on the road and objects equally, and the apparent contrast is little changed. By increasing the reflectivity of the road surface and hence the brightness of the light patches only, a much greater improvement in contrast is produced.

Hence at the Road Research Laboratory a good deal of effort has been devoted to the study of the reflecting properties of road surfaces.

Reflection characteristics of road surfaces

It is not much use suggesting to road engineers that they should always use one particular surface treatment and that then all will be well with their street lighting. Road surfaces must for reasons of economy and supply be made of local materials. What has been done is to produce data for a variety of road surfaces by means of which lighting engin-



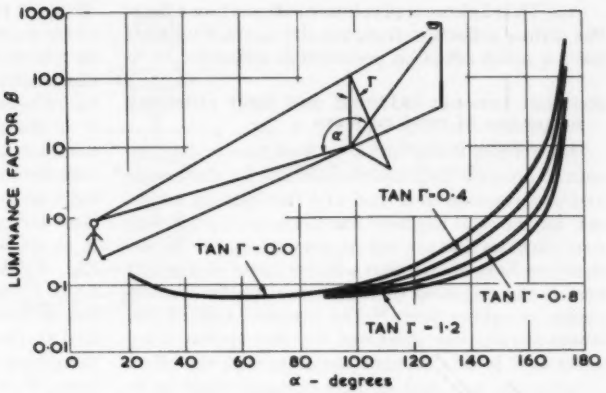


Fig. 2 (left). Definition of angles α *and* Γ *used in handling road surface reflection characteristics. Fig. 3 (right). Reflection characteristics of a dry rolled asphalt surface, with precoated chippings according to B.S.594.*

eers and others can themselves calculate the road brightness and the revealing power obtainable with existing or projected street-lighting installations. Unfortunately the luminance factor*, β, of a surface depends on three co-ordinates, the angles of incidence, reflection and azimuth, and cataloguing the luminance factor in terms of three angles is a formidable business. However, by developing the work of Bloch,[8] Christie[9] was able to show that, within the range of conditions that are of importance in the street-lighting problem, a good approximation to the exact result can be obtained by using only two co-ordinates, if these are carefully selected. For this purpose the angles α and Γ defined in Fig. 2 have been used. Reflection at a point directly between the observer and the lantern depends mainly on α and the fall off to the right and left of this point depends mainly on Γ. All the necessary data for a surface are therefore contained in a single set of curves such as Fig. 3. This approximation not only simplifies the presentation of data but also facilitates the calculation of the brightness of the road surface in a complete street-lighting installation.

The reflecting properties of a fairly representative sample of road surfaces have been investigated in dry weather and expressed in this new form. The results have already been used by a number of research organizations and designers of street-lighting installations and it is expected that they will be used more extensively when they are incorporated in a document now being prepard by the International Commission on Illumination (CIE).

It has not been considered necessary to study wet-weather reflection characteristics in the same way. The most important point in this case is whether the surface texture of the carriageway is coarse enough to prevent it becoming flooded and thus cause the brightness pattern to degenerate into a series of narrow streaks. It has been found that a medium surface texture corresponding to an average texture depth of about 0·013 in.* is required to ensure a reasonably uniform road surface brightness in light rain.[10]

As a result of all this work the dependence of the light reflection characteristics of a road surface on its physical characteristics is better understood. It is a matter of common observation that the bright patch produced by a street lantern on a dry surface is roughly T-shaped, the head of the T running across the road opposite the lantern and the tail of the T extending towards the observer. Surfaces which reflect diffusely give patches with a wide head and a short tail. Surfaces which reflect preferentially give a long tail and a small head.

The main findings from the research described above are:

(*i*) That surface texture—both the coarse or large-scale textures arising from stones in the surface and the fine texture of the tops of the individual stones —determines whether the surface reflects diffusely or preferentially when dry.

(*ii*) That coarse or large-scale texture determines the extent to which the brightness patch degenerates into bright streaks in wet weather.

* The ratio of the luminence (brightness) of the surface under the specified conditions of illumination and observation to the luminance of a perfect diffuser illuminated in the same way.

* Texture depth is measured by pouring a known volume of fine sand on to the surface and spreading it into a circular patch so that the valleys are filled in to the level of the peaks. The volume of sand divided by the area of the sand patch is the texture depth. It is the average thickness of the sand layer.

(*iii*) That lightness of colour of the surface affects the diffuse reflection from the dry surface without having much effect on preferential reflection.

Relation between skidding and light reflecting properties of road surfaces

The surface texture of a road surface is the concern of both the engineer responsible for the design and construction of a road and the lighting engineer, for the road engineer has the task of providing road surfaces that are not slippery when wet. Investigations have shown that a major cause of slipperiness is the polishing of roadstones by the scuffing action of rubber tyres.[11] The rounded tops of the stones are slippery when wet, but also appear shiny when dry. It was thought therefore that the effect of the newer non-skid surfaces of roads might be to reduce the amount of preferential reflection. To test this, measurements have been made on a number of roads with a special photometer and with apparatus for measuring the anti-skid properties.[12]

A photograph of the photometer is given in Fig. 4; it is portable and can be used in daylight. It is designed to estimate the brightness of road surfaces at the particular point P in Fig. 5 when illuminated by a lantern at L. The height of the lantern is 25 ft., the height of the observer's eye 5 ft. and the distance between observer and lamp standard 400 ft. P is the point of mirror reflection at which the angles of incidence and reflection are the same and therefore equal to 85·7°. The photometer directs light on to the road surface at this angle to the vertical and measures the amount of light glancing off it at an equal angle to the vertical, as shown in Fig. 6. The quantity calculated from the reading given by the instrument is the luminance factor of the surface under the conditions of measurement, that is, the number of times the surface is brighter than a perfect white diffuser under the same conditions. It is here referred to as the 'glancing-angle luminance factor', and it is a reliable measure of the length of bright patch between the lantern and the observer, produced by preferential reflection. For example, the luminance factor for the compressed rock asphalt which gave the long patch in Fig. 5 was 210 while that for the bituminous sand carpet which gave the short patch, was 6.

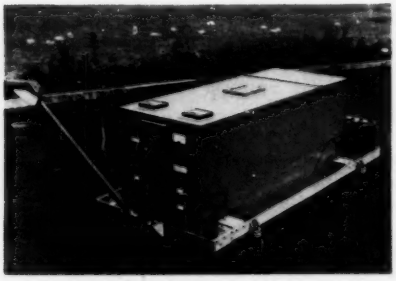


Fig. 4 (*above*). *Portable photometer used to measure preferential reflection from road surfaces* (*i.e. reflection at a glancing angle*).

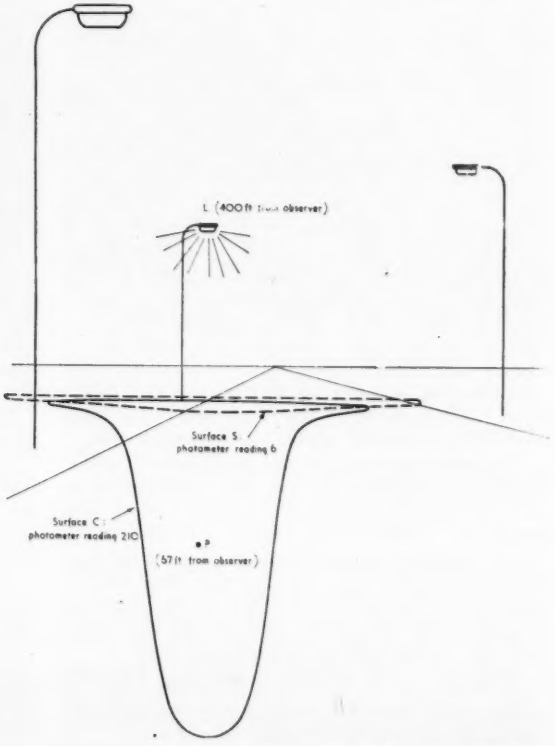


Fig. 5 (*right*). *The portable photometer gives the relative brightness of road surfaces at the point P due to the lantern L. The diagram also shows the shape of the bright patches produced by a uniform light source on two extreme types of surface. Surface C: an old polished rock asphalt. Surface S: a fine-textured bituminous carpet with a sandpaper finish.*

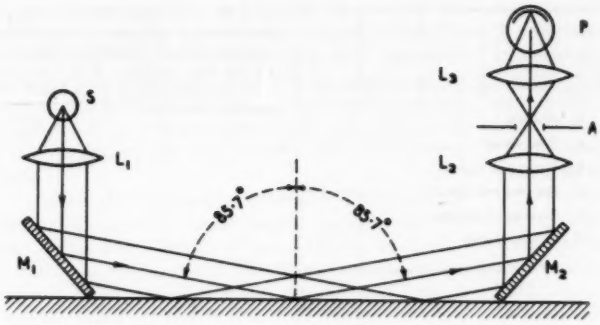


Fig. 6. Diagram of portable photometer for measuring preferential reflection (i.e. reflection at a glancing angle).

S	:	Lamp with small filament
$L_1 L_2 L_3$	:	Lenses
$M_1 M_2$	:	Mirrors
A	:	Small aperture (to limit angles of reflection studied)
P	:	Photocell

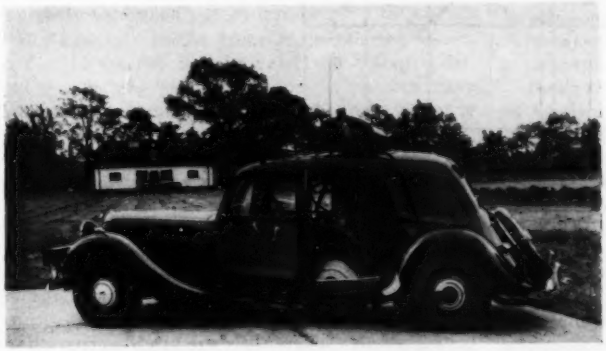


Fig. 7. The Road Research Laboratory skidding testcar.

The apparatus used to measure the skidding resistance of the wet surface is shown in Fig. 7. The force acting on a smooth tyre free to revolve is measured when the tyre is dragged at a small angle to the road surface so that it slips. The test wheel carrying the tyre is housed within the wheelbase of the car shown in the photograph. In carrying out a test the road is wetted from a tank on the roof and the wheel is swung about a vertical axis through an angle of about 20° to the direction of travel. From measurements of the wheel loading and the sideways thrust developed a measure of the skidding resistance is derived; this is called the 'sideway force coefficient'. This coefficient usually falls as the speed of the car increases but for the purpose of this investigation the sideway force coefficient at 30 mile/hr. is used.

Fig. 8, which gives the results obtained on a wide variety of road surfaces, shows that there is a marked tendency for the high values of luminance factor on a road when dry to be associated with low values of sideway force coefficient at 30 mile/hr. when wet and for surfaces with a high sideway force coefficient to have a low luminance factor.

Although there has been a definite improvement in the general standard of skidding resistance in recent years, and very smooth surfaces with coefficients of about 0·2 at 30 mile/hr. have largely disappeared,[13] still higher coefficients, of at least 0·5 at 30 mile/hr. under wet conditions, are needed

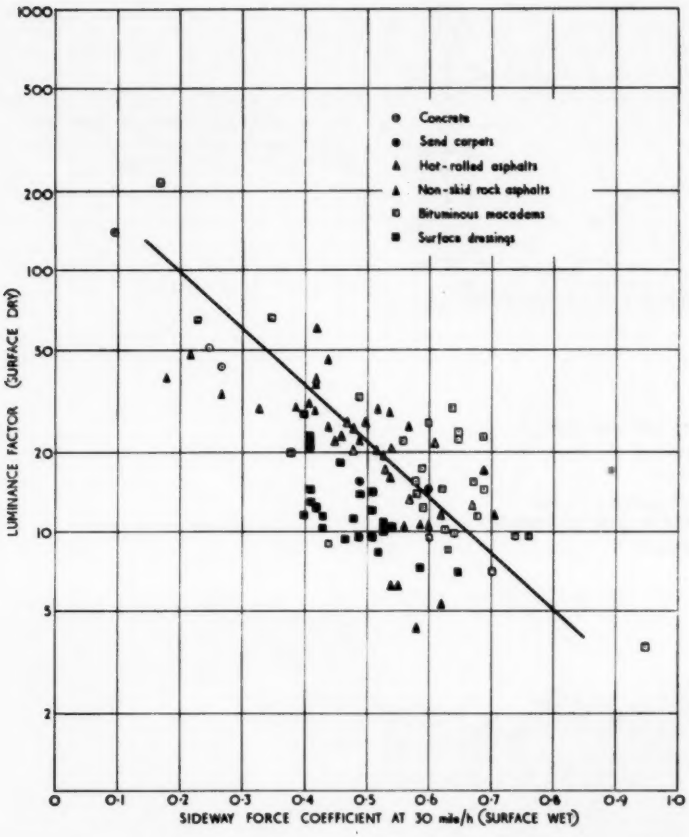


Fig. 8. The relationship between preferential reflection from the dry surface and the skidding resistance of the wet surface. The line has been drawn by eye to indicate the general tendency.

to meet the requirements of faster moving vehicles with better brakes. As can be seen from Fig. 8, the change from a coefficient of 0·2 to a coefficient of 0·5 is associated with a reduction in luminance factor from about 100 to about 25.

To meet these changes in the road surface, lighting engineers have to reconsider the advisability of continuing to use high-angle lighting. In the 1930s when roads were frequently smooth it was possible to light a road surface by means of specular reflection, very economically, using widely spaced lanterns emitting most of their light only slightly below the horizontal. These rays were reflected from the surface which appeared well lighted and glare, although considerable, was tolerable, because of the high surface brightness. Now, these road surfaces no longer exist and lighting engineers can no longer rely on preferential reflection to produce the necessary high brightness.

Unfortunately the effect of these changes has not been fully realized in time and high-angle installations are sometimes still being erected which cause severe glare. Such lanterns are no longer justified unless possibly where there are bright surroundings such as light-coloured buildings. Continental practice favours cut-off lighting (in both the street-lighting and the vehicle-lighting fields) and our street lighting frequently appears excessively glaring when compared with good continental installations.

Lantern arrangements

Present-day surfaces not only require a different light distribution, they also require more light. This has been recognized by public lighting engineers who have gradually reduced spacings between lamps and have increased the light flux provided per unit length of road. The change in road surface reflection characteristics has, however, emphasized a shortcoming in our group A lighting practice, namely the absence of adequate provision for deal-

ing with roads of increased width. At present the usual practice is to use the same type of lighting installation for all road widths up to 44 ft., namely, a staggered installation of lanterns sited over or close to the kerb at a height of 25 ft. and a spacing of about 120 ft. The arrangement is naturally much less satisfactory on wide roads than on narrow roads.

Consider the brightness patterns obtained with a medium-angle beam-aeroscreened installation on a road 30 ft. wide. With the smooth type of surface formerly employed the bright patches would merge longitudinally (see Fig. 9 (*a*)), but with a typical modern rolled asphalt the tails of the patches are now too short for successive patches on the same side of the road to merge. Moreover the heads of the patches do not spread right across the road (see Fig. 9 (*b*)). The result is a disconcerting dark pattern zig-zagging across the road. Fig. 10 shows a photograph of such an installation.

The most promising way of improving the pattern appears to be to extend the transverse spread of the lighter patches. If the heads of the patches can be made to cover the full width of the road the task of detecting unlit objects on the carriageway is greatly simplified.

For example, in the group B installation shown in Fig. 11, by the use of a very light-coloured diffusely reflecting surface, the bright patches have been made to extend right across the road; visibility is exceptionally good for such an installation, although the average luminance is not exceptionally high. The remaining, essentially transverse, dark bands appear to be much less disturbing than the zig-zag dark pattern.

There are two reasons for the effectiveness of such a transverse brightness pattern. Firstly, even small objects are certain to appear against some part of one of the bright patches; for example, if an object 100 ft. ahead of the observer is more than about 2 ft. 9 in. high it will cover a complete span length of the installation, i.e. one bright and one dark band. Secondly, because of the extreme simplicity of the regular transverse pattern, it is relatively easy to see where the brightness pattern on the road is broken by the silhouette of the object. (Fig. 13 shows a very extreme case of a transverse brightness pattern, and illustrates how a tall object, such as a pedestrian, may be seen against several bright bands.)

The present standard arrangement appears to serve very well on roads about 25 ft. wide, but on wider roads more generous installations seem desirable. One possible basis on which to work would be to magnify the brightness pattern on the road in proportion to the road width (i.e. use similar patterns) keeping the actual brightness levels the same. To do this both the mounting height and spacing of lanterns would have to increase in proportion to the road width, and the intensity of the lanterns in proportion to the square of the road width. The light flux per unit length of road would then be proportional to the width, that is, the light flux per unit area would be constant.

It would be useful if the mounting height could be kept equal to the road width but this would lead to the necessity for very tall columns on very wide roads and difficulties (of maintenance, etc.) arise with columns more than about 35 ft. tall. However, by judiciously varying the overhang and the spacing, other equally effective patterns could be obtained with slightly smaller mounting heights, say, 30 ft. mounting heights for roads 30–35 ft. wide, and 35 ft. mounting heights for roads 35–40 ft. wide with opposite arrangements on still wider roads. High mounting heights are commonly used in other countries and Fig. 12 shows the slender 40 ft. columns used on a motorway in Italy.

Siting of street-lighting columns

The siting of the columns that support street-lighting lanterns may require further study in the future, especially if the number of columns per mile is increased.

Research work carried out in the United States of America has shown that obstacles off the carriageway, but close to it, discourage drivers from making use of the full width of the road. In Great Britain it has been found that the proportion of vehicles with their nearside wheels within 4 ft. of the kerb fell from 37 to 30 per cent when concrete columns were placed 18 in. from the kerb of a busy three-lane road. The effect of columns mounted close to the carriageway is therefore to reduce the effective width of the road.

Another disadvantage of siting columns close to the edge of the carriageway is the increased severity of accidents involving vehicles leaving the road. In about 3 per cent of all fatal accidents to drivers and passengers or to motor-cyclists the vehicle or machine hit a lamp post. A study of the road accidents in the Metropolitan Police District for January and June 1956 suggests that 1¼ per cent of all people killed or injured are occupants or riders of vehicles that have collided with a street-lighting column mounted at the side of the road.[12] The actual number of columns involved in such accidents has been estimated at about 550 per year in the Metropolitan Police District, but the total number of columns damaged must be considerably greater, as not all collisions result in injury to occupants of the vehicle.

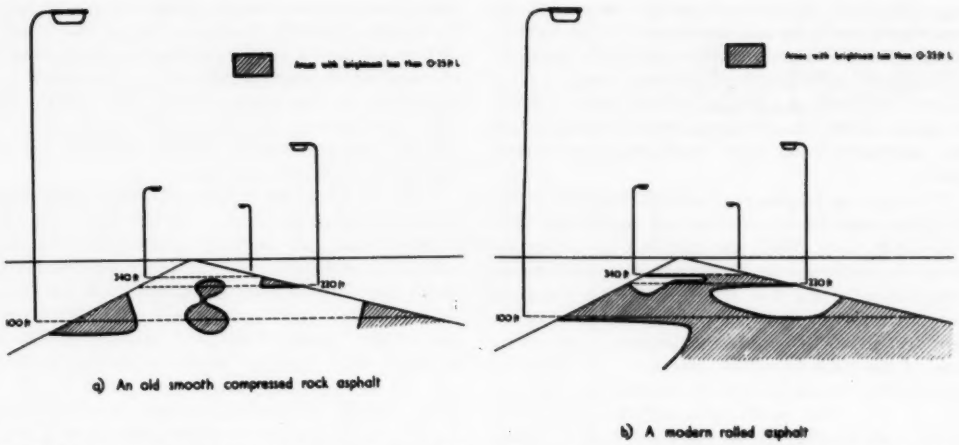


Fig. 9. *Brightness pattern produced by a medium angle beam (areoscreened) installation using* 140 *watt sodium lamps. Road width* 30 *ft.*

The Effect of Improvements in Street Lighting

The Laboratory has studied accident frequencies before and after the provision of improved street lighting at 64 sites on roads in various parts of Great Britain.[14]

Before the improvements, most of the roads had been lit to a poor or fairly poor standard with gas or electric filament lamps. In almost every case the new lighting conformed to the British Standard Code of Practice for Traffic Routes;[15] the majority of the installations were of discharge lamps—140-watt sodium, 240-watt fluorescent or 400-watt mercury.

The accident data for each site were obtained through the co-operation of local authorities and the police and the data related to periods of up to three years before and after the change. Table 1 shows the reduction in the number of accidents in

Fig. 10. *Medium-angle aeroscreened installation on road* 30 *ft. wide. Surface: rolled asphalt. Light source:* 400-*watt mercury. Spacing:* 117 *ft. Mounting height:* 25 *ft.*

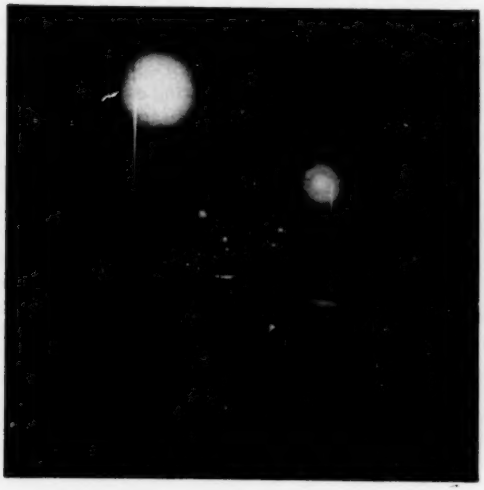
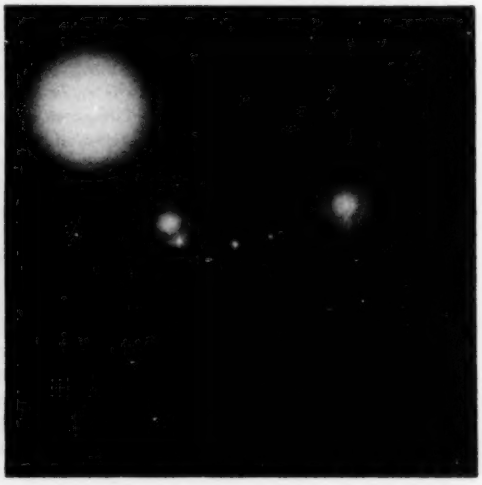


Fig. 11. *Group B installation with very light-coloured diffusing surface. (Heads of bright patches extend completely across the road which is* 24 *ft. wide.)*



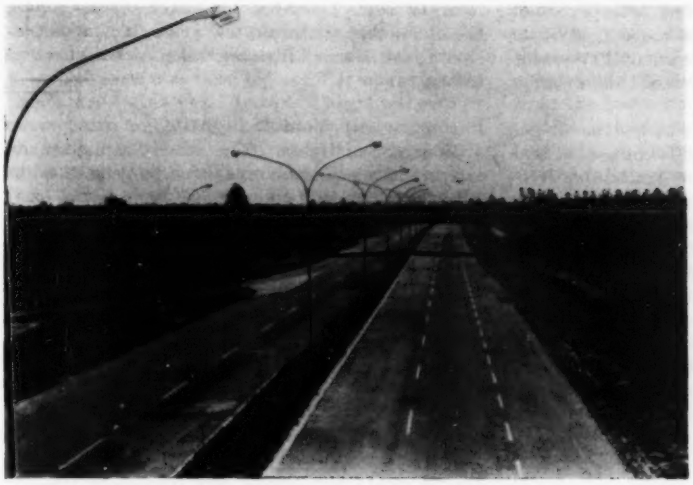


Fig. 12. Tall columns (about 40 ft. in height) on a motorway in Italy.

Table 1

Effect of lighting on injury accidents (64 improvements)

Number of accidents in darkness fell by 20 per cent.
Number of accidents in daylight rose by 14 per cent.

Estimated reduction in accidents in darkness

	per cent
1. All injury accidents	30
2. Accidents to pedestrians	45
Other injury accidents	23
3. Fatal accidents	50
Serious accidents	33
Slight accidents	27

which a pedestrian was injured, the number of accidents in which no pedestrian was injured, and all injury accidents together.

The reduction in the number of injury accidents at night from what was expected was 30 per cent and this reduction is highly significant. There was some evidence that fatal and serious accidents were reduced more than slight accidents but these differences could easily have arisen by chance. There was no evidence that any one type of lighting (mercury, sodium, etc.) provided greater benefit than any other.

Economic benefits

On the 64·5 miles of road included in the investigation 100 accidents per year were being prevented by relighting, or 1·55 per mile of road per year. It has been estimated[16] that relighting the roads studied reduced accidents costs by about £704 per mile of road per year which is only a little less than the total annual cost (including capital repayment) of the new lighting (about £800 per mile at 1958 prices), and is certainly greater than the increase in the annual cost of the lighting. Thus from the point of view of the community the modernization of the lighting can be considered as fully justified on economic grounds alone. Such calculations do not, of course, take into account the humanitarian aspect of the accident saving, nor the other benefits of better lighting.[14]

Speeds

It is sometimes suggested that improvements in street lighting tempt drivers to go faster with the result that the road is no safer than before. The figures just quoted show quite conclusively that even if the first half of the above statement is true the conclusion is not. In fact, at three sites it was found that although average speeds increased (by 2·1 mile/hr. for private cars and by 1·1 mile/hr. for commercial vehicles), injury accidents were reduced by about 31 per cent;[12] this reduction agrees well with the value found at the sixty-four sites.

Experimental Low-cost Street-lighting System on Main Roads Outside Built-up Areas

Main traffic routes outside built-up areas are usually unlit, and visibility at night on these roads is generally poor when there is traffic in both directions. When driving beams are used glare is of course severe but, even when correctly adjusted meeting beams are used, seeing distances are still very restricted. To overcome these difficulties the

Road Research Laboratory has been trying out a system that is less powerful and cheaper than group A lighting which may be too expensive to use on all main roads. The experimental system is designed to enable drivers to proceed more safely on meeting beams.[12]

The system was erected on a three-lane single-carriageway road 30–33 ft. wide. It consists of centrally-suspended cut-off lanterns containing 400-watt mercury lamps at a spacing of 270 ft., three times as long as that usually adopted. Fig. 13 shows how the road appears to a driver using his meeting beams and how a tall object well beyond the range of the meeting beams, is silhouetted against several bright patches.

Cut-off lanterns are used because with this system it is essential to reduce glare to the minimum. Central suspension was chosen to help spread the heads of the bright patches across the full width of the road.

Accidents

The reduction in the numbers of night accidents resulting in personal injury or damage which have occurred in comparable periods of 2½ years before and after the introduction of the experimental lighting is encouraging. On the experimental section they have fallen from 7 to 3 and on the control section have increased from 9 to 20.

The apparent reduction in accidents is, however, not statistically significant, and the lighting has recently been extended in length. It is hoped, therefore, that, within a few years, it will be possible to reach a definite conclusion on the effect on safety.

Vehicle Lighting

Modern headlights are a far cry from the oil lamps and acetylene lamps fitted to vehicles some fifty years ago, but today there is the same basic problem that was being recognized and tackled in those early days of motoring—how to eliminate dazzle and yet provide adequate visibility with a minimum of discomfort to drivers from glare. The basic difficulty is that with ordinary light the solution must be a compromise between visibility and glare.

To obtain a satisfactory main beam is not difficult; it is a matter of determining the light distribution required to enable the driver to see objects in his path. Provided the motorist is prepared to fit the necessary equipment, any reasonable requirements can be met. With dipped or meeting beams, however, questions of principle arise which are best illustrated by comparing the two schools of headlighting practice—the Anglo-American and the European. The Anglo-American meeting beams are dipped and deflected to the nearside, whereas the European meeting beams are sharply cut-off. The main difference is, however, that in the Anglo-

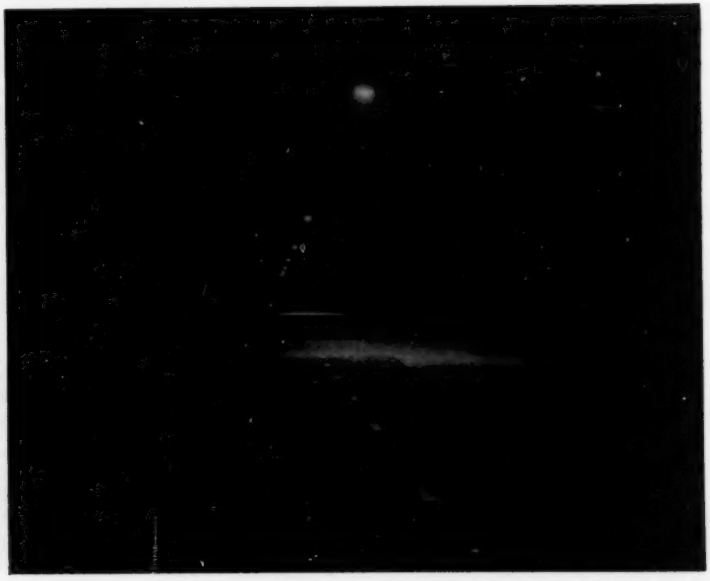


Fig. 13. Experimental long-spaced cut-off lighting system on a main road outside a built-up area.

American school of thought emphasis is on seeing distance, glare being the secondary consideration, and in the European school glare is considered the more important. The original symmetrical European beam has now been replaced by what is called the 'unified European beam'. The new beam is asymmetric and the cut-off line on the nearside of the beam has been raised so that it makes an angle of 15° with the horizontal plane. The effect of this is to allow more light to be directed along the nearside of the road, while retaining the comparatively glare-free characteristic in the off-side of the beam. Apart from the sharpness of cut-off, both the methods lead to roughly the same type of light distribution.

American four-lamp system

In 1958 a four-headlamp system was introduced in the USA, one pair of lamps being mounted on each side of the vehicle. All four lamps contribute to the driving beam and two lamps provide the meeting beam. The main advantages claimed for this arrangement are that compromises, which are necessary to produce a meeting and a driving beam from the same lamp, are no longer necessary, and that closer control of the light within the meeting beam is possible because the appropriate filaments are now at the true focal points of the reflectors.

Performance of meeting beams

To design improved meeting beams it is necessary to be able to test, and if possible, to predict their performance. Two experimental methods are used; in one, the distance is measured at which objects can be seen, and, in the other, general performance and comfort are assessed by a panel of observers.

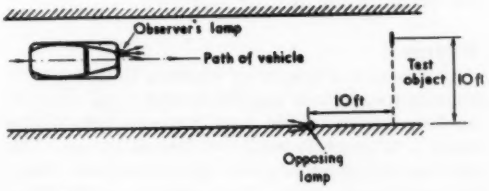
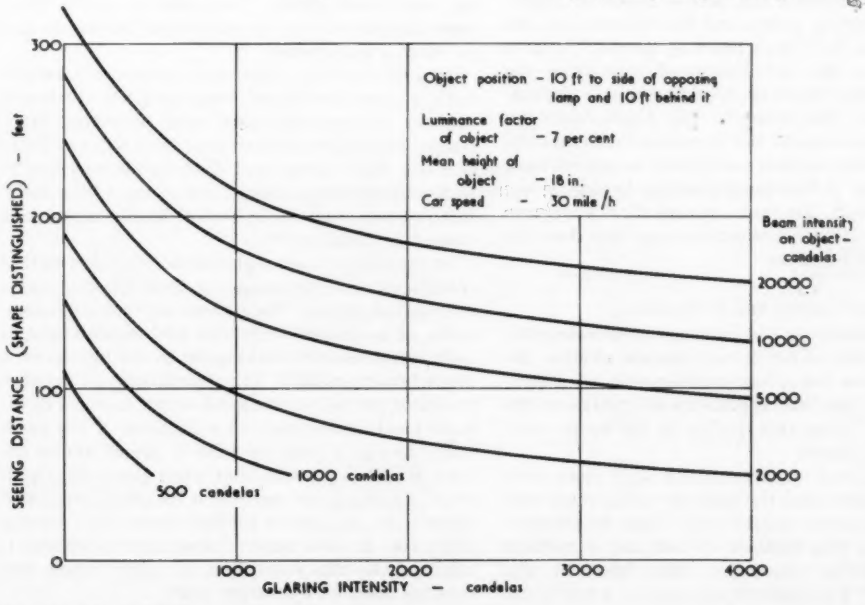


Fig. 14 (left). Layout of visibility tests.

Fig. 15 (below). The relation between seeing distance, beam intensity directed at an object, and glaring intensity.



Distance at which an object can be seen

At the Road Research Laboratory a simplified form of the method originally developed by Roper and Howard in America,[17] has been used.[18,19] A car with an observer is driven at 30 mile/hr. towards a stationary car with headlights switched on to provide the glare source. A test object is placed 10 ft. behind the stationary vehicle as shown in Fig. 14. This is almost the worst position for seeing it and hence measurements under these conditions give minimum seeing distances. Even this method of measuring the performance of a meeting beam is tedious. Measurements were therefore made with beams having a uniform distribution to obtain a general relation between illuminating intensity, glaring intensity and seeing distance for the test arrangement, from which the performance of actual road beams could be predicted.

The relation obtained from a large number of tests is given in Fig. 15, where the seeing distance is given for a range of intensities directed towards the object and of glaring intensities.

The basic data given in Fig. 15 can be extended to different road widths and object positions and to curved roads by means of the Stiles-Holladay law which states that the effect of a glaring light is directly proportional to the illumination at the observer's eyes and inversely proportional to the square of the angular separation between the glare source and the line of sight.[20] Using this relationship the performance can be calculated of Anglo-American meeting beams and the symmetrical and asymmetrical European meeting beams,[21] from a knowledge of the distribution of light from the headlamps; the results are used to compare alternative systems. For example, the Anglo-American meeting beams reveal the important nearside objects sooner and are less susceptible to misaim than the symmetrical European meeting beams. When correctly aimed, the new asymmetrical European beam reveals nearside objects sooner than does the current British system.

Tests of general comfort and performance

The measurements and calculations of seeing distance dealt with so far do not indicate whether the the beam gives the driver confidence in his ability to choose the best lateral place for his vehicle on the road, and to judge this quality in the beam, road tests are advocated.

The usual way of carrying out such tests is to drive a car fitted with the lamp on public roads and to assess its merits subjectively. There are obvious objections to this method of test and a method which overcomes these has been used at the Laboratory.[22] Two vehicles are used on a test track half a mile long with a curve at each end. Large obstacles are set up at the edges of the track and smaller ones in the middle. Each vehicle is fitted with the two types of headlamps which are to be compared. On completion of a systematic series of test runs each driver completes a questionnaire and notes his preference. The tests are run on wet and dry surfaces, water being supplied by a tanker fitted with a spray bar.

It was found that the British system was preferred to the European symmetrical system in almost all cases, particularly on wet roads where the European beam produced very bright reflections on the road surface. In addition the 'flashing' of the sharp cut-off beam caused by the pitching of the oncoming vehicle was found to be disturbing.

It was observed that the driver's preference was influenced considerably by the distribution of light in the meeting beam. Broad beams, which lit up the kerbs or grass verges, were preferred to narrower ones even although the narrower ones might be of higher intensity; and this preference is reflected in the design of the modern headlamp.

Surveys

One aspect of headlamp research to which early attention was given was the condition of lamps as used by drivers on the road. Surveys showed that there is a great diversity of beams in use. This diversity arises mainly from bad aiming, bad focusing, and deterioration. Two kinds of survey have been carried out: (*i*) by subjective judgments and (*ii*) with a glaremeter.

In early surveys, observers, driven in a vehicle with a correctly-dipped lamp in good condition, visually assessed the glare from oncoming headlamps. These tests showed that most drivers did in fact dip their lamps and that dazzle was due to badly-aimed lamps. About one in ten of the headlamp systems and one in five of the passlamps were classed as dazzling.[23]

In the later surveys a glaremeter was used so that conditions could be compared more reliably over a long period of time. The glaremeter[24] consists essentially of a photoelectric cell and recording gear sufficiently sensitive to respond to the light from a dipped beam at 300 ft. The apparatus is mounted in a vehicle, parked on the grass verge, facing a right-hand bend in the road. At a distance of 100 yards from the car, a detector tube is placed across the road in such a position that when the front wheels of an oncoming car run over it its lamps are aimed slightly to the offside of the observation vehicle (Fig. 16). In this way a close approximation is obtained to the conditions of glare when two vehicles meet on a straight road.

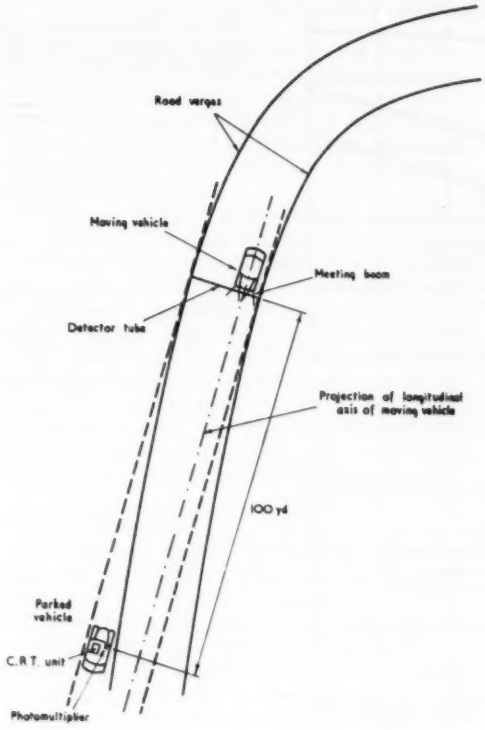


Fig. 16. Layout for measurement of glare of vehicle meeting beam.

The proportions of vehicles of different types using three kinds of meeting beam in 1955 are given in Table 2; whereas over half the cars and vans were using the double-dipping system, over half the heavy commercial vehicles still favoured the passlamp system.

The glare measurements of meeting beams made in this survey are shown in the form of distribution curves in Fig. 17. This figure shows that, in 1955, 35 per cent of double-dipping lamps were within the 1,000–2,000 cd. range, 54 per cent were above it and 11 per cent were below it. The curve for single nearside lamps shows that 23 per cent were within the 1,000–2,000 cd. range, 62 per cent above it and 15 per cent below the range. Thus uniformity is more nearly achieved with double-dipping lamps than with the single nearside lamp system. The passlamp system shows the greatest variation, with only 18 per cent within the limits 1,000–2,000 cd. and 71 per cent above and 11 per cent below this range.

Adjustment and maintenance of lamps

Headlamps will only be satisfactory if they are aimed correctly. Surveys of aim,[25] including the

Table 2
Relative proportion of meeting beams in use in 1955

Type of vehicle	*Type of meeting beam*	*No. of meeting beams*	*Percentage of meeting beams*
Cars and vans	One headlamp	267	31
	Two headlamps	492	57
	One passlamp	89	10
	Other types	20	2
	All types	868	100
Heavy commercial vehicles	One headlamp	354	34
	Two headlamps	106	10
	One passlamp	577	55
	Other types	8	1
	All types	1,045	100

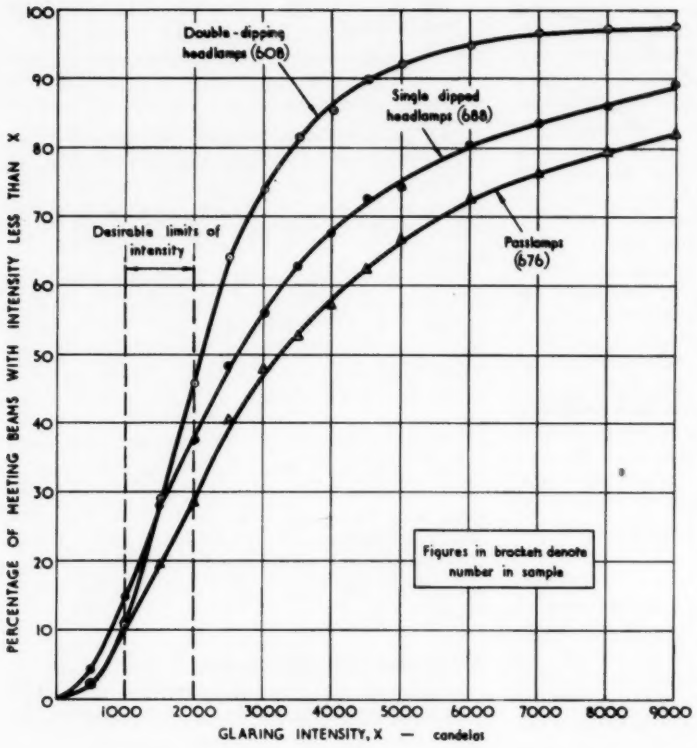


Fig. 17. The distribution of glaring intensities from headlamps and passlamps in 1955.

results obtained at the pilot testing station of the Ministry of Transport and Civil Aviation at Hendon, have shown that the standard of aim among headlamps is poor and that the headlighting system is one of the most neglected items of equipment on the vehicles in Great Britain.

At present there are no official regulations on the subject of headlamp aim beyond the broad requirement that the beams from all anti-dazzle systems should be deflected downwards. In the United States limits are defined, and recommendations have been made for appropriate limits for this country.[26]

Apart from the adjustment of the aim of a lamp, the condition of the lamp has a bearing on night driving. Lamps with dull and tarnished reflectors scatter light in unwanted directions, with the result that the beams lose their usefulness and may at the same time be unpleasant to meet. In older lamps the same effect can be produced even with good reflectors if the beams are defocused. The remedies are obvious; in the case of old lamps, the replating of dull reflectors and focusing of the beams and, in the case of modern lamps, replacement of the light units.

Yellow and white light

Many motorists who have driven in France are of the opinion that driving at night is easier and safer in that country because of the yellow headlight beams used there. A simple comparison of this sort, however, may be misleading because, as we have seen, there are differences in headlight practice in the two countries other than the colour of the light.

A great deal of laboratory work has been done on the influence of coloured light on seeing. The evidence that influenced the French to legislate in favour of yellow light was critically reviewed by the Department of Scientific and Industrial Research as long ago as 1937,[27] and the evidence that less dazzle and greater ease of seeing are associated with yellow headlight beams was found to be inconclusive. In that review no account was taken of personal preference, which was regarded as a dis-

turbing factor impossible to calculate or to investigate experimentally.

More recent tests undertaken by the Road Research Laboratory[28] consisted of: (*i*) measurements on a test track of the distance at which a test object could be seen from a moving vehicle and (*ii*) tests in which drivers were asked to express their preference after driving cars fitted first with white and then with yellow headlights.

The measurement of seeing distances in yellow and white light in clear weather showed that a neutral-coloured object was seen almost equally well in light of either colour. The twenty drivers who took part in the tests, which simulated realistic driving conditions, were more or less equally divided in their preferences for one or other colour where the cars met under conditions of glare. In the absence of glare there was about a ten to one preference for white light. The fact that emerged most clearly from the study of preferences is that most of the drivers preferred their own beam to be white.

Polarized light

As mentioned earlier, headlamp designers are faced with conflicting requirements—the provision of adequate light and the elimination of dazzle. Only a compromise is possible with ordinary light but by polarizing the light from headlamps it is possible to design a system which, at first sight, offers a complete answer to the difficulties.

With this in mind the possibilities of using polarized light have been carefully investigated.[29,30] With modern polarizers, the polarizer and analyser reduce the effective beam intensity of the lamp to about one-fifth of the initial unpolarized intensity for all objects except the lightest in colour. However, the loss is small compared with the reduction in the apparent glaring intensity of the oncoming polarized beam, and the system is capable of providing a marked improvement in seeing conditions. Difficulties which confront the introduction of the system are the transition period during which polarized and normal systems would be on the road at the same time, the replacement of the existing toughened-glass windscreen, which is itself optically active, by one of laminated glass, and the protection of other road users without polarizing equipment from dazzle. One helpful clue in night driving is lost when polarized light is used, namely, the illumination of the atmosphere which gives warning that a vehicle is approaching near a bend or over a hill.

No large manufacturer or country has disclosed any intention of changing over to a polarized headlamp system. In America where this matter has been seriously discussed for many years it has been argued thus: if a driver fits such headlamps he does not help himself but other drivers. The man who buys a new car, probably does so once a year. If a polarized light system cost $100 he may have to invest $500, $600 or $700 before his philanthropy is fully rewarded—i.e. when most cars are fitted with polarized lighting systems. The encouragement of such far-sightedness is not without its difficulties in other spheres of life and does, at the moment, appear to be a serious difficulty in the vehicle headlighting field.[31]

Ways of overcoming this difficulty by using a combination of ordinary and polarized lighting during the changeover from ordinary to polarized light have been investigated but up to the present no acceptable system has been devised, despite widespread interest in the system.

Foglamps

There are advantages in using special lamps in fog and experiments have been carried out to find out how seeing in fog at night depends on the shape, cut-off and intensity of the beam and on the mounting height of the foglamp.[32]

The tests showed that a wide fan of light aimed to illuminate the width of an average road is desirable. The lamp providing the beam should be mounted about 2 ft. above the road, and the beam should have a reasonable cut-off to its upper edge. The wide beam enables a driver to position his vehicle on the road with confidence, and to make use of the reflector studs or the white line in the centre of the road, while still retaining correct station on the nearside of the road. It is inevitable because of the width of the beam that its maximum intensity is low, but this is not normally a disadvantage in fog. There is room for improvement in many foglamps now marketed.

Measurements in fog at night showed that with yellow or white beams of the same intensity there was no difference in the distance ahead at which objects could be identified. The question of colour is thus one of personal preference.

Other aspects of vehicle lighting

Before concluding my paper there are certain other important aspects of vehicle lighting which have been investigated at the Road Research Laboratory which should be mentioned. For example, twin rearlights were found to be necessary for accurate estimation of distance, and were subsequently required by Regulations. An examination of vehicle reflectors showed that some reflectors on the market return only one-thousandth of the light returned by good quality ones and Regulations are

now in force to ensure that improved reflectors are fitted to new vehicles.

In another investigation semaphore-arm trafficators have been compared with flashing indicators. It was found that flashing indicators must be several hundred times brighter than a semaphore-arm indicator in order to be as efficient, but that the best flashing indicators are superior. The use of amber for indicators at front and rear was found to be better than the use of red and white, and the need for good separation between rear indicator and stop lights was shown. These findings are now accepted by the industry and most British vehicles incorporate these improvements.

Conclusions

In presenting the present review of the work of the Road Research Laboratory in the field of street and vehicle lighting attention has been drawn to a number of problems still to be resolved and to many practices where improvement is possible. There is no doubt, however, that lighting in both spheres has an increasingly great contribution to make to road safety.

Progress in some directions has been hampered by the existence of accepted practices and by specifications drawn up in days when roads, road conditions and vehicles were very different from what they are today. Fortunately, however, there is at present a great awareness of the need for these practices and specifications to be revised in the interests of safety and comfort to the road user and to the easy flow of traffic, and it is to be hoped that the day will not be far distant when night travel is considerably safer and more comfortable than it is today.

Finally I should like once more to thank the Society for inviting me to give this paper and to thank also my colleagues, particularly Messrs Moore, Christie and Jehu, for the help they have so readily given to me in preparing it.

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